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FREQUENCY MODULATED MAGNETIC TAPE RECORDING AND PLAYBACK INSTRUMENTATION SYSTEM

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U. S. NAVAL ORDNANCE LABORATORY
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FREQUENCY MODULATED MAGNETIC TAPE RECORDING AND PLAYBACK INSTRUMENTATION SYSTEM

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ABSTRACT: The development of a frequency modulated system for the recording of pressures and accelerations resulting from high explosive detonations is described. The intelligence from a pressure gage or accelerometer gage frequency modulates a carrier frequency, and after being multiplexed this FM signal is transmitted by cable and remotely recorded on a magnetic tape recorder. In playback the output of a magnetic tape reproducer is fed through band pass filters, which separate out the various carrier frequencies of the multiplexed signal; from here each filtered signal is fed to a discriminator unit which converts the frequency modulated signal to an amplitude signal. Finally this amplitude signal is presented to a string oscillograph which produces a photographic record of the signal.

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This report is part of a classified report issued as report NOLR-1167. The numbering system used in this report is accounted for by the fact that it is part of a more extensive report. The purpose of this report is to declassify and circulate on a wider basis certain parts of this more extensive report which deal with instrumentation development of general interest. It may be stated that the recording system herein described was successfully used on large scale explosion tests. The accelerometers used in conjunction with this recording system are described in unclassified NAVORD Report 2712. This work was carried out by the Explosion Effects Division of the Explosives Research Department under Task NOL-187.

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CHAPTER 5

RECORDING AND PLAYBACK

This chapter describes in detail the units comprising the overall FM magnetic tape recording and playback instrumentation used for the recording of pressures and accelerations resulting from large explosions. The general features of the system are depicted in block diagram form in Fig. 5.1 through Fig. 5.4.

5.1 DESIGN CONSIDERATIONS:

(1) Number of Measurements - One hundred gage signals were to be recorded.

(2) Remote Control - For personnel safety and safety of equipment, remote control was required.

(3) Simplicity - The large number of measurements to be made indicated the desirability of uncomplicated equipment with a minimum number of parts and simple field adjustments.

(4) Reliability - The large expense involved and the need for the information sought, made it mandatory that all the required data be obtained.

(5) Time - Very little time was available for the design, procurement and testing of the system.

5.2 DESIGN FEATURES

(1) Frequency Modulation - The FM system was used. With this system, small interference could be expected from amplitude modulating signals such as from power lines or other equipment.

(2) Multiplexing - Because of the large number of measurements to be taken, the multiplexing system was used. This permitted the use of only twenty channels per shot for signal transmission; each channel contained five carrier frequencies, frequency modulated by five different gages.

(3) Magnetic Tape Recording - This mode of recording was chosen because of its freedom from the need of critical field adjustments, simplicity of operation, and adaptability to remote control.

(4) Cable Telemetry - In the interest of simplicity, cable was used to transmit the signal from the field oscillators to the instrumentation trailer. Radio telemetry would have unnecessarily complicated the field instrumentation with transmitters, antennas, and receivers.

(5) Reliability - To enhance the reliability of the overall recording system and to insure obtaining the maximum amount of significant data, wide use was made of "back-up" units. Four complete, identical, and independent banks of equipment were used in each trailer, each bank operating five channels, one for each of five stations. The stations for each bank were selected so that in case of failure of one complete bank, recorded signals from no more than two distances would be lost. The five stations lost were so staggered as to minimize this loss (see Table 5.1). Each recorder had its inputs paralleled with the inputs of a second recorder to minimize the loss of records in case of tape or recorder failure. Each motor-generator set was powered by paralleled banks of batteries. Reference and timing signals were generated from a multiplicity of sources and recorded on two tracks of each tape. (These signals were used as fiducials, therefore they were common to all recording banks.)

TABLE 5.1

Station Distribution to Instrumentation Banks

Distances	Instrumentation Bank 10 ft Depth	20 ft Depth	30 ft Depth	Distances Lost With Failure of Bank 1	2	3	4	Stations Lost With Failure of Bank 1	2	3	4
1	1			X				X			
2	3	4	2						X	X	X
3	3					X				X	
4	4						X				X
5	2	3	1					X	X	X	
6	4						X				X
7	2				X				X		
8	4	1	3					X		X	X
9	2				X				X		
10	1	2	4					X	X		X
11	1			X				X			
12	3					X				X	

5.3 PERFORMANCE CHARACTERISTICS:

(1) Frequency Response from D.C. to approximately 150 cps on the 3.9 kc channel, and to approximately 1,000 cps on the 14.5 kc channel. The upper frequency limits of any particular channel were limited by the frequency response of the gages used on that channel.

(2) Dynamic Range approximately a factor of 100, realized by the use of "back-up" gages.

(3) Resolution sufficient to read down to 1/20 of nominal full scale gage range. This resolution was limited by the noise - "wow-and-flutter" - inherent in the magnetic tape recording and playback mechanisms.

(4) Accuracy of reading the records varied from approximately ± 3% for signals produced near the nominal gage range to approximately 10% for the signals which were nearer 1/20 of the gage range.

(5) Recording Time of 15 minutes was availalbe.

5.4 FIELD UNITS:

5.4.1 Gage

The frequency modulating elements in both the acceleration and pressure gages consisted of iron-core inductors whose actual inductance value varied with the instantaneous position of a high permeability pad relative to the inductor core.

The accelerometers were manufactured by Schaevitz Engineering Company of Camden, New Jersey and are described in detail in Chapter 4 of this report; the pressure gages were manufactured by Wiancko and are described in detail in a Ballistics Research Laboratory report now under preparation.

5.4.2 Gage Cable

Each gage was connected to its oscillator circuit by a 10, 20, or 30 foot length of two conductor, low capacitance, shielded cable, RG-22/U. This cable had two particularly desirable features - low linear capacitance, 16 mmf per foot, and rugged mechanical construction. Low capacitance cable was a requisite since the cable capacitance comprised part of the tank capacitance of the oscillator; good design considerations called for as much as possible of the tank

capacitance to be of a fixed type. Even with this design criterion, on the 14.5 kc channels with the 35 foot length of cable (required for the 30 foot deep gages) only approximately 10% of the total tank capacitance was fixed. However, the rugged construction of the cable made this situation tolerable. Under hydrostatic and shock testing up to 1,000 psi levels, negligible change in cable capacitance was observed.

5.4.3 Oscillator-Amplifier[1] (Fig. 5.5)

The oscillator-amplifier unit was designed by the Vitro Corporation[2] in accordance with specifications supplied by NOL. It consisted of five input circuits and a combined output circuit. The input oscillator circuits were of the Hartley shunt feed type, with one section of a dual triode tube (12AU7) serving in the oscillator. The Hartley circuit was chosen because of its inherent stability; shunt feed was necessary in order to prevent the introduction of objectionable magnetic bias into the accelerometer coils. The second half of the tube was directly coupled to the oscillator section and served as the amplifier stage. The signals were coupled to the transmission cable, MCOS-6, by means of output transformers which provided the proper impedance match between the oscillator-amplifier units and transmission cables. The secondary windings of the output transformers of the 3.9 kc, 5.4 kc, and 7.35 kc circuits were in series across the output terminals. However, the signals from the 10.5 kc and 14.5 kc circuits were mixed and superimposed on the output through a bridge circuit (Fig. 5.6). This was necessary in order to reduce the cross-modulation between these two signals to an acceptable minimum value. It was found that without this bridging network, a 4 kc difference frequency would be produced by these two frequencies which could cause objectionable interference in the 3.9 kc band. Interference between all bands was kept to a minimum by designing the oscillator-amplifier circuits so that the total harmonic distortion was less than 3%. In this way, for example, the second harmonic of the 5.4 kc circuit was kept from distorting the signal in the 10.5 kc band.

The filament and plate power necessary to operate the units was furnished by means of the multi-conductor MCOS-6 cables. All power originated at the trailer.

The oscillator units were extremely stable and free from extraneous influences. For a change in B+ voltage from 225 volts to 325 volts the oscillator frequencies changed approximately 17 parts per million per volt on all channels except the 14.5 kc, where the change

[1] See Technical Report No. 28 of the Vitro Corp. of America, "Instruction Book - Oscillator Set TT-1/36-A and Housing.
[2] Formerly the Kellex Corporation.

was approximately 50 parts per million per volt. The frequency change due to filament voltage variations was approximately 10 parts per million per volt. Temperature changes from 20°F to 130°F resulted in frequency changes of 10 parts per million per degree F. Tests in an air gun for producing transient accelerations were made with the units operating normally while high acceleration shocks up to 50 g were applied. There were no discernible effects on the output frequency at accelerations below 30 g, and only a 15 cps change at 50 g. All the above frequency deviations were considered negligible over the limited range of voltages, temperatures and shocks to which the oscillators were to be subjected.

The oscillator units were not designed primarily for repeated operations, therefore the use of long-life components was not justified. However, operation during use had to be dependable and it was very important that as many circuits as possible function properly at that time. The circuits had a minimum number of components to reduce the chances of component failure. Except for the common filament and plate supplies, a failure in one circuit would not seriously affect the operation of the other circuits.

5.4.4 Transmission Cable

The cable used for the transmission of the signal from the field stations to the instrument trailers was a standard Navy type, MCOS-6. This cable consisted of two shielded pair and an unshielded pair of conductors, the overall cable being approximately 1/2 inch in diameter and covered with a neoprene jacket. The characteristic impedance of the signal conductors was approximately 70 ohms; for maximum signal transmission the cable was terminated at both ends with this impedance value. The attenuation of signals varied with the frequency of the signal carrier, the attenuation for the 3.9 kc carrier being 1.1 db per 1,000 feet and for the 14.5 kc carrier being 1.6 db per 1,000 feet (Fig. 5.7). (The oscillator-amplifier units were designed to equalize this variation by providing higher outputs for the higher frequency channels than for the lower frequency channels.) The conductors were utilized as shown in Fig 5.7. The individual pairs of leads were used for separate functions so as to achieve simplicity and reliability, and the signal leads were paralleled to reduce attenuation.

It was estimated that approximately 250,000 feet of cable would be required in Operation Jangle. This cable was available on reels each holding approximately 1,500 feet which made it convenient for laying (Fig. 5.8). To facilitate the task in the field of joining the individual cables to provide the proper lengths, connectors were attached to the ends of the cable at NOL. All that was required in the field was to join the connectors and waterproof the joint (Fig. 5.9). In this way, good electrical continuity was obtained along with strong mechanical linkage all with a saving in manhours in the field over either solder or cold splice methods.

5.5 INSTRUMENTATION TRAILER UNITS:

All recording and power equipment and necessary auxiliary units were housed in van-type trailers. These units are described below and the units directly associated with the recording of the signal are shown in Fig. 5.10.

5.5.1 Auxiliary Signal Units

(1) Distribution Panel (Fig. 5.11) - This panel served as a master distribution panel. It fed filament and plate voltages to the five stations of each bank. It also distributed the output signals of each oscillator set, through two impedance matching transformers in each signal channel, to a recording channel in each of two different recorders. The primary circuits of the transformers were connected together and matched to the characteristic impedance of the MCOS-6 cable, and the individual secondary windings were matched to the input impedance of each recorder. An attenuation network was added to the primary circuit of the transformers to reduce the signal level input to the recorders.

(2) D. C. Power Supply Panel (Fig. 5.12) - This panel received 36 volts D.C. to operate five DM-36 dynamotors (Fig. 5.13). The 300 volt filtered outputs of these units were fed to the Distribution Panel for coupling to the transmission cables and thence to the field oscillator sets. Dynamotor plate supplies were used in this operation rather than electronic power supplies because of the greater simplicity, and the ready availability of the battery source.

(3) D. C. Junction Panel - Power for this panel was received from the same 36 volt battery banks that powered the motor-generators. The five output receptacles distributed power to the D.C. Power Supply Panel.

(4) Filament Supply Panel (Fig. 5.14) - This panel received 115 volts A.C. which operated an auto transformer adjusted to produce a 145 volt output. This voltage level was needed to compensate for the voltage drop incurred over approximately 1-1/2 miles of cable in furnishing 130 volts A.C. at the filament transformer in each oscillator set. Each output receptacle fed only one cable and was individually fused with a slow-blow fuze. In this way, short circuiting of one oscillator set would not affect the other oscillator sets operating off the same auto transformer.[3]

[3] For more detail on the above four panels, see Vitro Corporation Technical Report No. 29 "Installation Manual - Distribution Panels TF-1/36-A, J-1/36-A, DY-1/36-A, and J-2/36-A".

(5) A. C. Junction Panel - All A.C. power for the auxiliary units and the recorders was distributed from this panel. It received power from its associated motor-generator set.

The above panels were connected by means of cables in order to facilitate isolation of any particular component for trouble shooting purposes. A sufficient variety of types of connectors were used so that improper connections were not likely.

5.5.2 Magnetic Tape Recorder (Fig. 5.15)

The recorders were modified Ampex Model 301 commercial magnetic tape sound recorders similar to those used by the NOL group on Operation Greenhouse.[4] The salient features of these recorders are listed below:

(1) Seven separate heads in one assembly were employed to record seven channels simultaneously on 1/2" wide magnetic tape. Each channel track was 0.050 inches wide and separation between tracks was 0.020 inches.

(2) Frequency response of the recorders was flat within $\pm$ 3 db from 1 kc to 18 kc.

(3) Signal to noise ratio was greater than 20 db below a 3% distortion recording level. Cross-talk between adjacent channels was at least 45 db down.

(4) Tuning fork controlled capstan motor drive was employed to keep tape speed variations to a minimum resulting in less than 0.1% r.m.s. "wow-and-flutter".

(5) Remote control was provided for all necessary operations - application of power, start of tape transport, and recording of signal.

(6) Only the recording (not playback) operation was possible on this recorder. Further simplifications and fool-proof features of the recorders were the elimination of erase heads and the use of only forward speed at 30 inches per second.

The recorder contained seven identical two-stage amplifiers with inputs located on the front of the unit (Fig. 5.16). The power for this chassis was provided by the power supply chassis

[4]Greenhouse Report Annex 1.6, Part IV, Section 1; also "Instruction Book-Multi-Channel Magnetic Tape Recorder and Reproducer produced under Kellex Corp. Purchase Order SS No. 21223" by Ampex.

below it. For each channel the record amplifier had separate Bias Control and Signal Level Metering Jacks, Bias Adjustment and Record Level Adjustment Controls.

The power supply unit (Fig. 5.17) was of the conventional full-wave high vacuum type with adequate filtering. The high frequency (70 kc) bias supply also was located on this chassis. This push-pull oscillator had very low harmonic content in its output.

The capstan motor amplifier unit (Fig. 5.18) contained a 69 cps tuning fork which controlled the frequency of an amplitude limited oscillator circuit. The output from the oscillator was subsequently amplified and used to operate the capstan motor drive.

The prime requisite of magnetic tape recorders when used in frequency modulating systems is to keep the speed variations of the tape to a minimum. Speed variations are equivalent to frequency modulations of the signal and are, therefore, reproduced along with gage signals as extraneous and objectionable noise. The bouncing of the tape on the recording head also produces objectionable speed modulation of the tape; this "flutter" was kept to a minimum by the careful design of all parts in the tape transport mechanism and some mechanical filtering by the use of tension arms. However, irregularities on the tape surface and dust on the tape and heads were difficult to control or eliminate. As a result, the noise due to "flutter" varied from recorder to recorder and from shot to shot.

5.5.3 Auxiliary Units

(1) Timing Oscillator (Fig. 5.19)

In addition to the gage signals, calibration signals were recorded simultaneously on the tape. A composite signal of two frequencies was produced by each of two Timing Oscillator units. One unit produced a standard unmodulated frequency of 400 cps and a modulated center frequency of 2,300 cps. The other unit produced a standard unmodulated frequency of 1,000 cps and a modulated center frequency of 3,900 cps. Although only one standard frequency and one modulated frequency was required, two Timing Oscillator units were used to insure against failure of either of the units. The standard frequency signals were required to adjust the tape speed on playback to that speed which would reproduce the recorded information faithfully. These frequencies were produced by tuning fork oscillators of the General Radio type 723.

The modulated frequencies centered at 2,300 cps and 3,900 cps were produced by phase shaft oscillator circuits. These frequencies were modulated by timing signals from Blue Box and relay sources. At minus 1 second, an EG&G timing relay signal produced a frequency

shift in the oscillator. This signal was used as an aid in playback to automatically trigger the playback sequence; it could also be used as a fiducial marker since its time with respect to zero could be accurately determined and it was common to all recorders. However, the Blue Box signals (photo electric signals), initiated by the visible detonation of the test explosive were used as the timing fiducial. Two Blue Boxes were used, each feeding its signal into the phase shift oscillators of each Timing Oscillator unit. These signals produced frequency shifts of opposite sense and different time durations from the minus 1 second signal.

In operation, the minus 1 second relay closed, triggering a one-shot multi-vibrator which then produced a 0.13 second pulse. To prevent multiple triggering due to possible relay chatter, a 1/200 ampere fuze was blown, thus opening the input circuit. At zero time, the Blue Box (or timing relay) closed and triggered another similar multi-vibrator which produced a 0.05 second pulse. The outputs from the two multivibrators were mixed and frequency modulated the phase shift oscillator producing 5% frequency shifts.

(2) <u>Timing Oscillator Distribution</u>

The two output signals of each Timing Oscillator unit were fed into this Timing Oscillator Distribution Panel where all four signals were added by a resistive network. Eight outputs were provided carrying the composite signals to one head of each of the eight recorders. Each output was decoupled sufficiently to prevent interference among recorders.

(3) <u>Reference Oscillator</u> (Figs. 5.20 and 5.21)

An oscillator unit providing stable oscillations at the five signal frequencies used (3.9, 5.4, 7.35, 10.5 and 14.5 kc) was constructed to provide a convenient reference source for checking the frequencies of the field oscillators. As a second function, the mixed frequencies of the oscillator unit were recorded on one head of each recorder to provide a reference calibration signal during playback. As a third possible function, this signal was recorded with a view to using it in a tentative scheme for "wow-and-flutter" reduction. (This function was not realized on this operation because of the lack of time required to fully develop the design.)

The circuit for this unit consisted of five cathode-coupled 12AT7 oscillators, followed by five grounded grid amplifiers whose outputs were added linearly in a resistive network. Grounded-grid amplifiers rather than conventional amplifiers were used only because a coupling condenser was thereby eliminated. The low output impedance of the cathode-coupled oscillators, moreover, permitted direct coupling to the grounded grid amplifiers. Dropping resistors were needed to adjust the voltage level in the amplifiers for equal output voltages. A sixth triode amplifier for a modulated signal from the Timing Oscillator had its output added into the same network and the composite signal was then fed in parallel to four cathode follower output stages. The six amplifiers and four cathode followers were contained in five 12AX7 tubes.

Each cathode follower fed a recording channel in each of two tape recorders, the two output terminals being isolated by two 22 kilo-ohm resistors to prevent loss of signal to one recording channel if the other should become short circuited. The output from the driven cathode in each of the five oscillators was brought out to a separate terminal through an 8.2 kilo-ohm isolating resistor. Air-dielectric trimmer capacitors for each oscillator were located beneath these output terminals to provide fine tuning of the individual oscillators. The stability of these oscillators was approximately a factor of ten greater than that of the field oscillators.

(4) Filter Scope (Fig. 5.22)

In order to measure and inspect each of the five frequencies put out by each of the field oscillators, narrow-band-pass filters, tuned to the frequencies 3,900, 5,400, 7,390, 10,500, and 14,500 cps were needed. This function was provided by the "Filter Scope" which, in addition to permitting selective amplification at each of the five frequencies, permitted two signals, one from the field oscillator and the other from a reference source such as the Reference Oscillator, to be presented on a cathode ray tube for frequency comparison by Lissojous patterns. Both horizontal and vertical amplifiers, identically constructed, had separately accessible input and output terminals.

Each tuned amplifier stage consisted of a bridge-T feedback amplifier using a "cascoded" 12AX7 tube.[5] The deflection stage was 1/2 of a 12AX7, connected as a triode amplifier, while the output stage, also 1/2 of the 12AX7, was connected as a cathode follower. In both the horizontal and vertical amplifiers, six-position

[5] G. E. Valley, Jr. and H. Wallman, "Vacuum Tube Amplifiers," M.I.T. Radiation Laboratory Series, Vol. 18, McGraw-Hill, New York (1948) Chapt. 10.

selector switches permitted a choice of either non-selective amplification (position 6) or selective amplification at any one of the five standard frequencies (positions 1 through 5). Tuning of the bridge-T networks was accomplished by adjusting the set screw in each of the VIC inductors; gain and selectivity were controlled by adjusting resistors R_1 through R_5, each having a 5 kilo-ohm potentiometer for fine adjustment. As the value of each of these resistors increased, both the gain and selectivity increased; beyond a certain value, regeneration may occur and the adjustment had to be made so as to avoid this difficulty.

A voltage doubler power supply was used to provide both positive voltage for the amplifiers and negative voltage for the cathode ray tube.

(5) Field Operation Check Panel

The purpose of this check panel was to allow monitoring of the plate and filament voltages and currents being fed to the field oscillators and of the composite signal received from these oscillators without interferring with the operation of the system. The panel contained A.C. and D.C. voltmeters and ammeters which were switched into the appropriate circuits. A coaxial output connector was bridged across the signal leads to allow for monitoring of the oscillator frequencies and wave-forms. Two jumpers were used to insert the Check Panel between the MCOS-6 field cable and the Distribution Panel. The Check Panel was used only in initially setting-up the equipment and in trouble shooting. The presence or absence of plate and filament voltages and currents was made immediately evident and by noting the amount of current flowing in the plate and filament circuits, improper operation could be localized to particular components of the system.

(6) Field Cable Tester (Fig. 5.23)

Although all cable was carefully tested before leaving the Laboratory, to forestall difficulties caused by shortened, open, or low resistance cable, all cable was checked just prior to laying by a simple Cable Tester. This two-unit tester checked the most pertinent five combinations of leads in pairs by means of switching boxes and an ohmmeter.

(7) Blue Box (Fig. 5.24)

The zero timing signal was obtained from a Blue Box manufactured by EG&G. The circuit contained a vacuum phototube (929) sensitive in the visible region, coupled to a thyratron tube (2D21) by a small capacitor so that only a sharply rising light pulse, such as emitted by the fireball of an exploding charge, would trigger the thyratron. The firing of the thyratron produced a voltage step at its cathode which was used as the zero timing signal fed into the Timing Oscillator unit.

(8) Timing Relays

The timing relays were supplied by EG&G and were manufactured by Union Switch and Signal Co., Swissvale, Pa. Seven rack mounted relays were provided to initiate the 22 separate control functions for the complete recording instrumentation at the four specified times (Fig. 5.28).

5.5.4 Primary Power

Primary power for operating the field oscillators and the trailer instrumentation during the tests was provided by battery banks housed in the battery compartments of the trailers (Fig. 5.25). In this way, except for the few timing signals required from outside sources, complete independence of operation was achieved during the test. In addition, a stable, noise-free power source was realized which could be expected to be dependable throughout and after the blast.

The batteries used were 6 volt 175 ampere-hour lead storage batteries. Each bank of equipment was supplied by twelve batteries arranged in series - parallel to provide 36 volts with 350 ampere-hours capacity; this capacity allowed for at least two hours of continuous operation of the equipment. Each battery bank ran the five dynamotors in its associated instrumentation bank, and the motor generator which provided the A.C. power for this same instrumentation bank.

The motor generators (Fig. 5.26) had a load rating of 2.5 kva; this size was quite adequate since total power consumption for the complete instrumentation bank was approximately 1,500 watts. While operating under nominal full load, the output voltage and frequency of the generators were adjusted to 60 cps and 117 volts by means of rheostats prior to the tests; the stability of the motor-generators was such as to maintain these values during the unattended test operation.

The various controllers, switches, and relays necessary to properly couple power from the batteries to the generators and to the instrumentation were incorporated into the design (Fig. 5.27). These units also provided a ready means of connecting battery charging equipment to the batteries, and A.C. power from an external source, such as a gasoline generator or a commercial-type power line, to the recording instrumentation for use during setting-up procedures.

During the test operation, a minus 15 minute relay signal actuated the controllers which started the motor generators and supplied the D.C. to the dynamotors. At this same time, a time delay mechanism

was started. After 20 minutes of operation (15 minutes before zero to provide the required time for the equipment to reach stability and five minutes after zero), the time delay mechanism opened the controller circuits and cut both A.C. and D.C. power to the instrumentation.

5.5.5 Instrumentation Trailer (Figs. 5.29 through 5.32)

During the history of the project when test sites, instrumentation lines, and test conditions were not definitely determined, it became evident that a mobile instrumentation trailer would be of considerable aid in setting up the field program in almost any situation. Consequently, two van-type trailers were procured and outfitted identically. Each trailer was 32 feet 3 inches long, 7-1/2 feet wide, and 11-1/2 feet high. The trailer was partitioned into three compartments, one for batteries, one for the motor generators and controllers, and the third and largest compartment for housing the recorders, auxiliary panels, testing equipment, work benches and supply cabinets (Fig. 5.33).

The motor generators and the relay racks holding the electronic equipment were shock mounted to prevent vibrations and shock from adversely affecting the operation of the equipment. An air conditioning unit was installed in each trailer to provide favorable operation conditions for the equipment and personnel regardless of outside weather conditions. To provide accessibility to the backs of the rack mounted equipment, each bank of instrumentation was secured to a platform mounted on casters. Signal cables entered the trailer through small ports located in each side of the trailers; the outside power cable, which provided the lighting and outlet power, was connected to the trailer by means of an external connector. External connectors also were used to connect the battery chargers to the power source and the batteries. (The battery chargers were located outside the trailers because of space limitations and as a safety measure.) (Fig. 5.34).

5.6 RECORD REDUCTION (Fig. 5.35)

5.6.1 Reproducer (Fig. 5.36) - The playback unit was designed and constructed by the Ampex Electric Corporation to reproduce the tapes recorded on the Recorder unit. It consisted of four separate component units.

(1) Tape Transport Mechanism - This unit, basically, was similar to that of the Recorder, but it had a few additions. It had a selector switch for quick choice of mode of operation to facilitate signal location and playback. With the selector switch in the "play" position the tape traveled at a velocity of 30 inches per second (approximately the same speed as the Recorder). Three other modes of operation

were provided: Fast Forward, Fast Rewind, and Slow Rewind. The take-up tension arm on the Reproducer actuated a shut-off switch which automatically shut off the mechanism in the event of tape breakage.

(2) Reproducer Amplifier (Fig. 5.37) - This unit incorporated two identical playback amplifiers which allowed for simultaneous playback of any two channels by means of selector switches. Normally one amplifier was switched from head to head in order to reproduce the gage signals on five of the tracks; the second amplifier was set to play back the signal on the track which contained the standard reference frequency and timing signals. By means of a second output on this second amplifier circuit and a phone jack to allow for the insertion of a 400 cps or 1,000 cps filter, the standard frequency was made available for tape speed control.

(3) Capstan Motor Amplifier (Fig. 5.38) - This unit, located within the Reproducer console, was very similar to the tuning fork amplifier of the Recorder. Instead of a tuning fork, however, the signal being amplified to drive the capstan motor was supplied by a Wien bridge oscillator located inside the tape speed control unit.

(4) Tape Speed Control Unit (Fig. 5.39) - This unit, coupled to the Reproducer console by means of a cable, contained a stable 69 cycle Wien bridge oscillator. Two potentiometer controls provided fine and course adjustments of this oscillator frequency within a ± 3 cycle range.

In the playback procedure, the 400 cps (or 1,000 cps) standard frequency signal obtained from the tape was fed to the vertical input of a cathode ray oscilloscope. The signal from a local tuning fork oscillator, identical to the one used in the trailer for recording, was fed to the horizontal input thus forming a Lissajous pattern. The Tape Speed Control unit was adjusted until a stationary pattern was obtained. This was the indication that the tape speed in playback was the proper one to give faithful reproduction of all recorded signal frequencies. This scheme compensates for tape length variations caused by temperature and humidity variations between time of recording to time of playback. It also compensated for possible variations in tape speed during the recording process caused by faulty drive mechanisms. It was because of this speed control feature and indication of correct frequency reproduction that it was possible to calibrate the system frequency-wise during record playback, thus simplifying the field electronics.

5.6.2 Discriminator (Fig. 5.40) - The composite FM field signal from the Reproducer was fed into five Discriminator units, with parallel inputs, each unit containing a band-pass filter t[illegible] one of the carrier frequencies modulated by the gage signal. [illegible] the

Discriminator, the frequency modulated signal was converted into amplitude variations with time and was made suitable for presentation on a string galvanometer oscillograph.

The Discriminators were made by the National Machine Shop of Silver Spring, Maryland, and originally designed by the Applied Physics Laboratory of Johns Hopkins University for the Bumble Bee system.

The input stage of the Discriminator was a cathode follower having an input impedance of 1/2 megohm, preceded by an attenuator enabling utilization of input signals ranging in level from 10mv to 10v. Following the input cathode follower was a plug-in band-pass filter which allowed selection of the desired FM signal and provided rejection of all other signals. After filtering, the desired FM signal was amplified and limited, the limited signal actuating a pulse forming circuit which delivered one pulse for each cycle of the incoming signal. Each of these pulses triggered a one-shot multivibrator which returned to its rest state after a time interval equal to half the reciprocal of the center frequency of the selected FM signal. The return time of the multivibrator was determined by the circuit constants of a plug-in network augmented by a fine adjustment. By the proper choice of one of a number of such plug-in networks, the return time of the multivibrator was adjusted to correspond to the chosen FM signal for that gage channel - 3.9, 5.4, 7.35, 10.5, or 14.5 kc.

When the return time of the multivibrator was adjusted to correspond to the center frequency of the selected FM signal, the average voltage measured between the plates of the multivibrator tubes was proportional to the deviation of the signal from the center frequency. This averaging was performed by a low-pass filter inserted between the multivibrator plates and the following cathode followers. These were followed by another push-pull cathode-follower stage, providing a balanced output having an effective source impedance of 330 ohms. Overload protection incorporated in the output circuit automatically limited the output current to ±15 ma. With the output load 330 ohms, the load current was 10 ma when the FM signal deviated 7-1/2% from its center frequency.

The timing signal from the standard reference track of the tape was reproduced by means of a sixth discriminator operating on a center frequency of 2.3 kc or 3.9 kc.

5.6.3 <u>String Galvanometer Oscillograph</u> (Fig. 5.41) - The String Galvanometer Oscillograph unit changed the electrical signal outputs of the Discriminators into a visual and photographic presentation. This unit was manufactured by the Century Geophysical Corporation of Tulsa, Oklahoma. Although sixteen strings could be accommodated in this unit,

only six were used - one for each of the five gage signals played back simultaneously, and one for the timing fiducial signal.

The resonant frequency of the galvanometers was 200 cps and each had a resistance of 60 ohms and required an external shunt of 120 ohms for critical damping. These resistors and the network required to properly match the impedance of the galvanometers to the Discriminators were built on an auxiliary panel. This panel also provided attenuation of the signals into the galvanometers so as not to overload these elements.

The oscillograph unit contained a tuning fork controlled oscillator which produced 100 and 10 millisecond timing lines transversely across the eight inch wide photographic paper used. The paper used was Kodak Linograph 1127, selected because of its high sensitivity. The paper feed speed used was approximately 10-15 inches per second.

5.6.4 Calibration Oscillator (Fig. 5.42) - The function of the calibration oscillator was to provide for each of the five gage frequency bands a sequence of calibrating frequencies which when fed through the playback system, produced stepwise calibration marks on the photographic records. For convenience and accuracy, these calibration marks were made to appear during the one second interval preceding the zero time mark. The calibration sequence, which was obtained by means of an automatic stepping 5-pole, 22-position relay, corresponded to frequency deviations from center frequency in the order: 0%, +6%, +3%, +1.5%, +0.5%, 0%, -0.5%, -1.5%, -3%, -6%, 0%, +6%, +3%, +1.5%, +0.5%, 0%, -0.5%, -1.5%, -3%, -6%, 0%, the center frequencies being 3,900, 5,400, 7,350, 10,500, and 14,500 cps.

The basic oscillator design used a cathode follower coupled to a grounded-grid amplifier by means of a series resonant LC circuit. Each of the five oscillators used a single 12AT7 tube and contained a high-Q inductor with an appropriate set of capacitors tuned to the desired frequencies and selected in turn by a stepping relay. Positions 1 through 10 were connected so as to provide the first half of the calibration sequence while positions 11 through 20 were appropriately paralleled with the first ten positions so that the first half of the sequence was repeated. Positions 21 and 22 provided center frequencies again. The output of each oscillator was taken from the cathode of the cathode follower at an impedance level of something less than 200 ohms. In this way, cross-talk between the five calibration oscillators was minimized.

The power supply, constructed on a separate chassis (Fig. 5.43), was electronically regulated and used a "cascode" regulator circuit. In order to prevent cross-talk between the five oscillators and the playback signal, the B+ lead to the oscillators was disconnected except during the calibration interval. Low voltage

(up to 12 volts) D.C. for the relays was furnished by means of a full-wave selenium rectifier and this voltage was controlled by a Variac. In this way, the calibration cycle could be varied from 1/2 to 2 seconds. A connector was provided on the skirt of the oscillator chassis to feed low voltage D.C. to the sequencing unit chassis and to receive therefrom the triggering short-circuit for the stepping relay.

Under laboratory conditions, the stability of the oscillators was in the order of ± 2 to ± 5 cps over periods of several weeks. Under field conditions, this stability was not observed.

5.6.5 Sequencing Unit (Fig. 5.44) - In order to facilitate the playback of records and presentation in final form, a unit was constructed which controlled the necessary playback operations in orderly sequence. This unit had two modes of operation, "Automatic" which was normally used in playback, and "Manual" which was normally used in setting-up procedures. By means of this Sequencing unit the locally generated frequencies from the Calibration Oscillator unit and the recorded gage signals from the Reproducer were applied through the playback system in proper sequence and in synchronization with the string oscillograph operation.

With the unit set to "Automatic", the playback procedure was as follows:

The tape transport was started manually well before the appearance of signals on the tape. When the signal appeared, the Tape Speed Control was adjusted until a stationary Lissajous pattern was formed. Approximately 30 seconds were available for this manually performed operation before the automatic operation started. With the appearance of the minus one second signal on the standard reference track, a voltage pulse was formed in the Discriminator, and passed on to the sequencing unit. Here the signal was amplified before triggering a thyratron circuit. The thyratron output pulse initiated the calibration sequence by actuating the stepping relay in the Calibration Oscillator unit. Simultaneously, a five-pole, double-throw relay was actuated. This relay switched from the Reproducer output to the Calibration Oscillator outputs so that each of the five calibration signals was fed individually into the proper Discriminator. After the calibration cycle which had a duration of approximately one second, when the stepping relay came to rest again, the five-pole, double-throw relay switched back to the Reproducer output, thus feeding the gage signals into all five Discriminators simultaneously. Coincident with the start of the calibration cycle, the circuit providing for automatic operation of the string oscillograph was closed. This started the paper drive and illuminated the galvanometer mirrors and record identification numerals. After the gage signals on the tape were recorded, as evidenced by the meter movements on the Discriminators, the playback was stopped, the tape rewound, and the above procedure followed for the other gage signal tracks.

At times it was desirable to record on the string oscillograph only one of the gage signals making up the composite signal on a track. This was accomplished by the simple expedient of connecting only the required lead to the string oscillograph.

In "Manual" operation, the various operations described above were initiated by switches. In this way it was convenient to cycle the calibration oscillators one step at a time and to check and adjust the calibration frequencies to close tolerances. Also, it provided a means of initiating automatic operation when the minus one second signal circuit failed to operate.

5.6.6 Photographic Technique - The photographic paper obtained from the string oscillograph magazines varied in length from five feet to 150 feet depending on the number of tape runs that were made. For the shorter lengths, tray developing was used. For the longer lengths of paper, a portable automatic tank method was used (Fig 5.45). Because of the high photographic speed of the paper, to obtain best results, all loading and unloading of the magazines and developing of the paper was done in a darkroom without benefit of safe lights.

The paper was dried on a small, commercial drum dryer with an automatic paper feed and take-up device added (Fig. 5.46).

5.7 PERFORMANCE AND RECOMMENDATIONS:

The present over-all instrumentation system performed satisfactorily on Operation Jangle; however, improvements in design are indicated for future use so as to realize even better performance. The most serious shortcoming of the system was the low signal to noise ratio obtained in the field. Although the recorders and playback machines met or even exceeded specifications for "wow-and-flutter", less than 0.1% rms, in the laboratory, this figure was exceeded by as much as a factor of 2.5 in the field. For the most part, this was due to the ever-present dust problem and the inability to keep recording and playback heads, the capstans, idlers and magnetic tapes completely free of dust. However, even under laboratory conditions it would be advisable to decrease the "wow-and flutter", thus increasing the dynamic range of the equipment and obviating the need for "back-up" gages. This, of course, would free gage circuits for additional measurements.

This decrease could be accomplished in many ways - by redesigning the recorder and playback machines, by employing some "wow-and-flutter" compensation scheme, or by producing a larger signal. The redesign of the recorder and reproducer could proceed along the lines of developing smoother motor drives and better mechanical filtering possibly using compliance loops similar to those used in sound-on-film recording.

Compensation methods could be designed including servo-mechanisms to correct for "wow" and mixing and "beating" schemes for "flutter" reduction. It was this latter scheme that was attempted in the NOL instrumentation and abandoned temporarily because of the lack of time.

Essentially, it was a system to make "wow-and-flutter" a function of the frequency deviation produced by the acceleration or pressure phenomenon, rather than the carrier center frequency. Since the frequency deviation could be at most approximately 10% of the center frequency, a minimum noise reduction factor of 10 could be expected, with greater reduction for smaller signals. In this method, the compensation was accomplished in playback. The signal frequency was beat with the output of a local oscillator, the sum frequency filtered and passed into another non-linear mixer circuit. The unmodulated reference frequency from the tape also was fed into this mixer, the difference frequency filtered and passed into a discriminator where amplitude variations were produced corresponding to the original signal phenomenon. Early tests on this system were encouraging and further work should be undertaken.

Increase of signal to "wow-and-flutter" induced noise can be accomplished by producing larger signals. This indicates a gage development problem with a view towards increasing the frequency deviation produced by any given forcing function. (Of course, this would limit the spacing of adjacent bands, but this may not be detrimental in some applications.)

New gage development should also seek a linear end instrument as stated in Chapter 4. This would lead to a simple expansion of the playback system permitting more complete data reduction and enabling acceleration records to yield velocity and displacement data electronically.

In conjunction with decreased "wow-and-flutter" endeavors, work should be done on oscillator-amplifier design. In a multiplexing system it is important to keep intermodulation products at a low level so as not to cause interference in other bands. This indicates that the total harmonic content of oscillators and amplifiers should be low. The 3% level obtained in Operation Jangle was tolerable because it was masked by the "wow-and-flutter" noise; with better noise characteristics, lower harmonic distortion limits will have to be maintained.

The physical design of the trailer instrumentation could be improved by combining all the components included in one recording channel (exclusive of the Recorders) on one small chassis. Field experience showed very little need for trouble shooting on the trailer equipment thus eliminating the need for multiple-disconnect elements with its encumbering cabling.

A modification in the filament supply design would be advisable. At present, with only one transformer feeding the filaments of the five oscillator-amplifier units in one instrumentation bank, the output voltage of the auto-transformer is set to the optimum value for the mid-distance station. Because of the difference in lengths of cables and the resultant difference in line attenuation, some stations operated with an over-voltage, and others with an under-voltage. Although no tube failure or other adverse effects resulted from this condition, in future operations with possibly longer lines, detrimental voltages may be incurred at the extreme stations. Individual transformers for each station would eliminate this condition, and lead to a more reliable and flexible design.

As an aid to overall field operation and as a step toward coping with the dust problem, it is suggested that a trailer be outfitted to house the playback instrumentation. This trailer should also contain the photographic processing facility and it could contain the necessary laboratory work space and storage space for the project group.

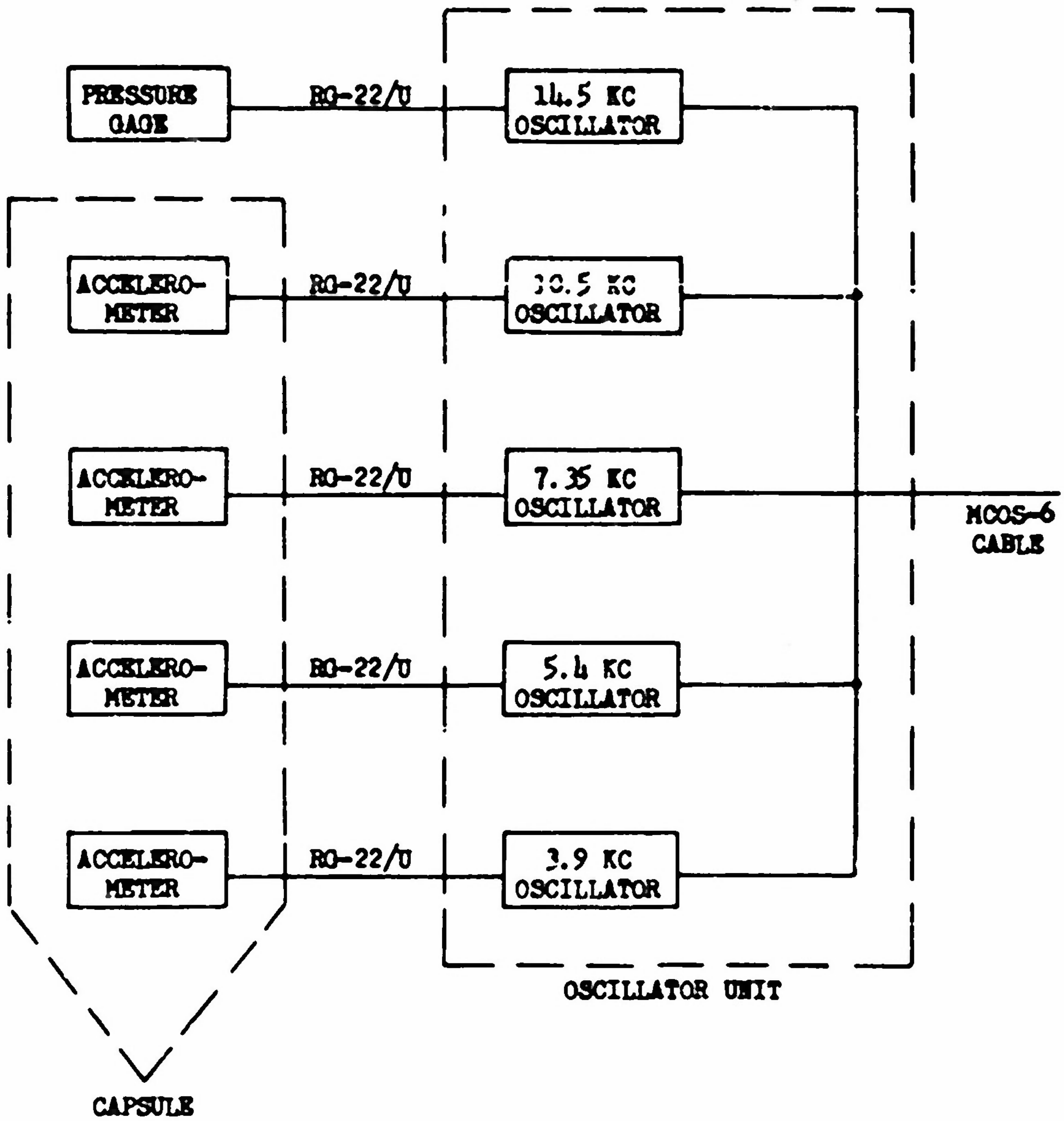


FIG. 5.1 TYPICAL STATION INSTALLATION

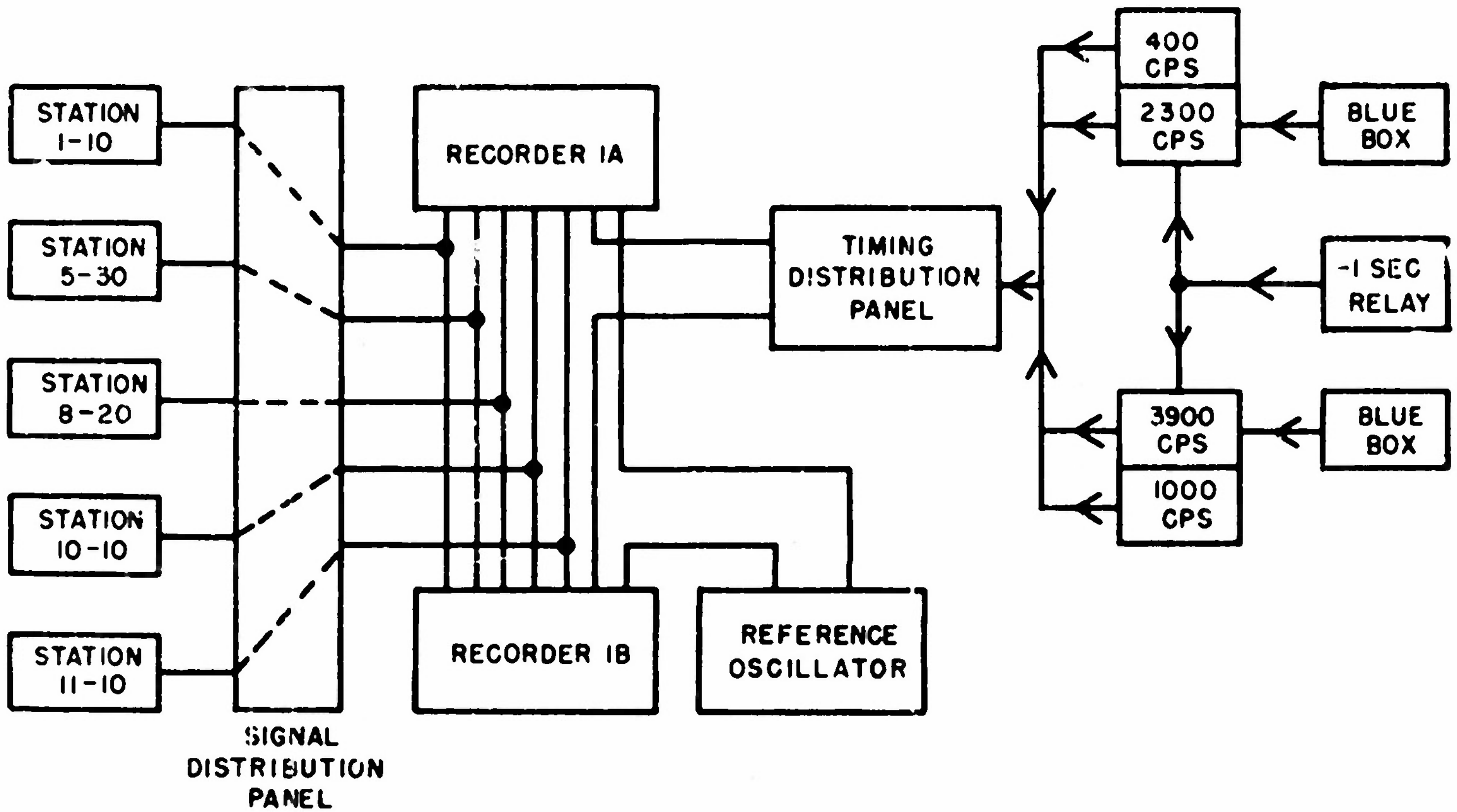


FIG. 5.2
SIGNAL DISTRIBUTION FOR TYPICAL BANK

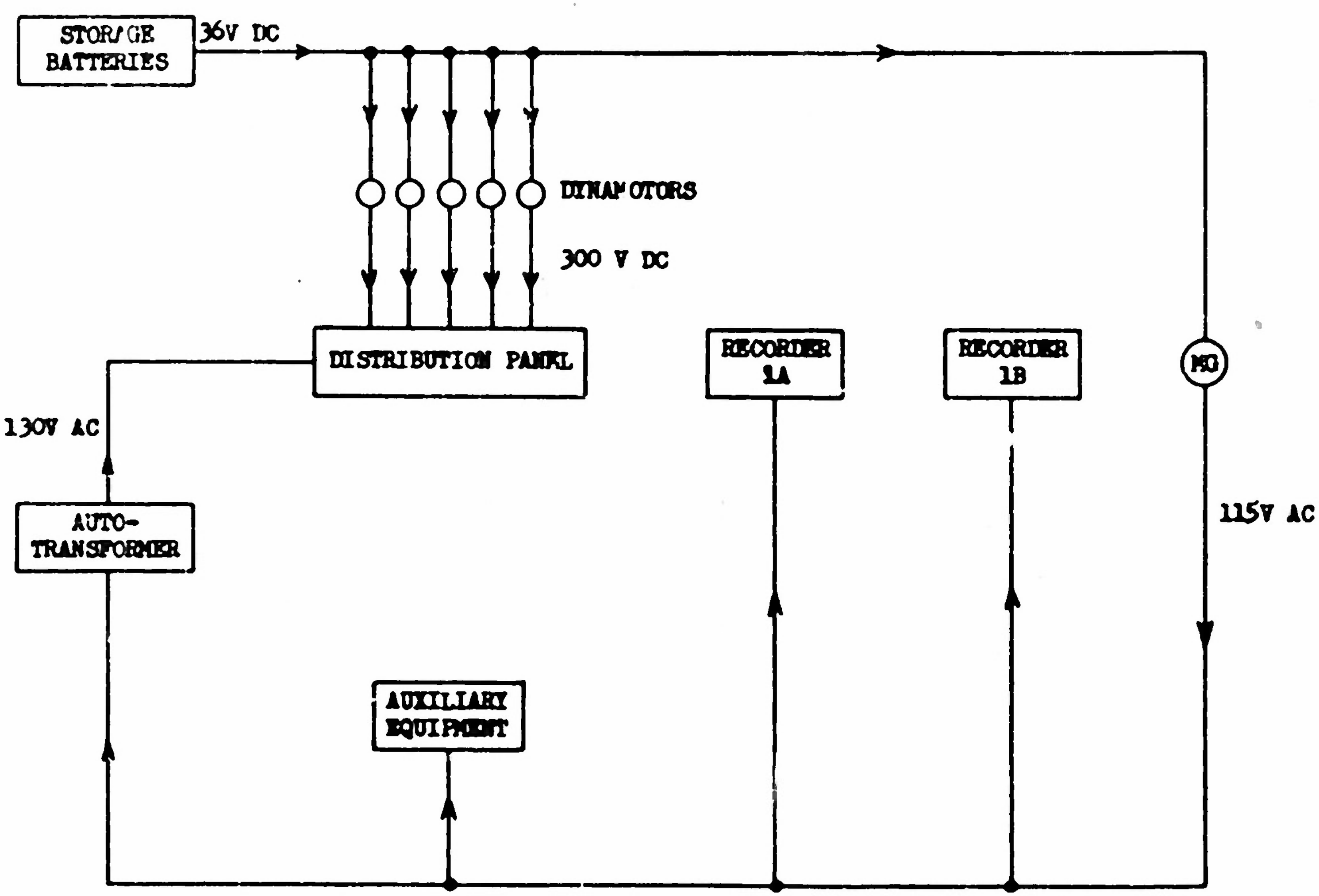


FIG. 5.3 POWER DISTRIBUTION FOR TYPICAL BANK

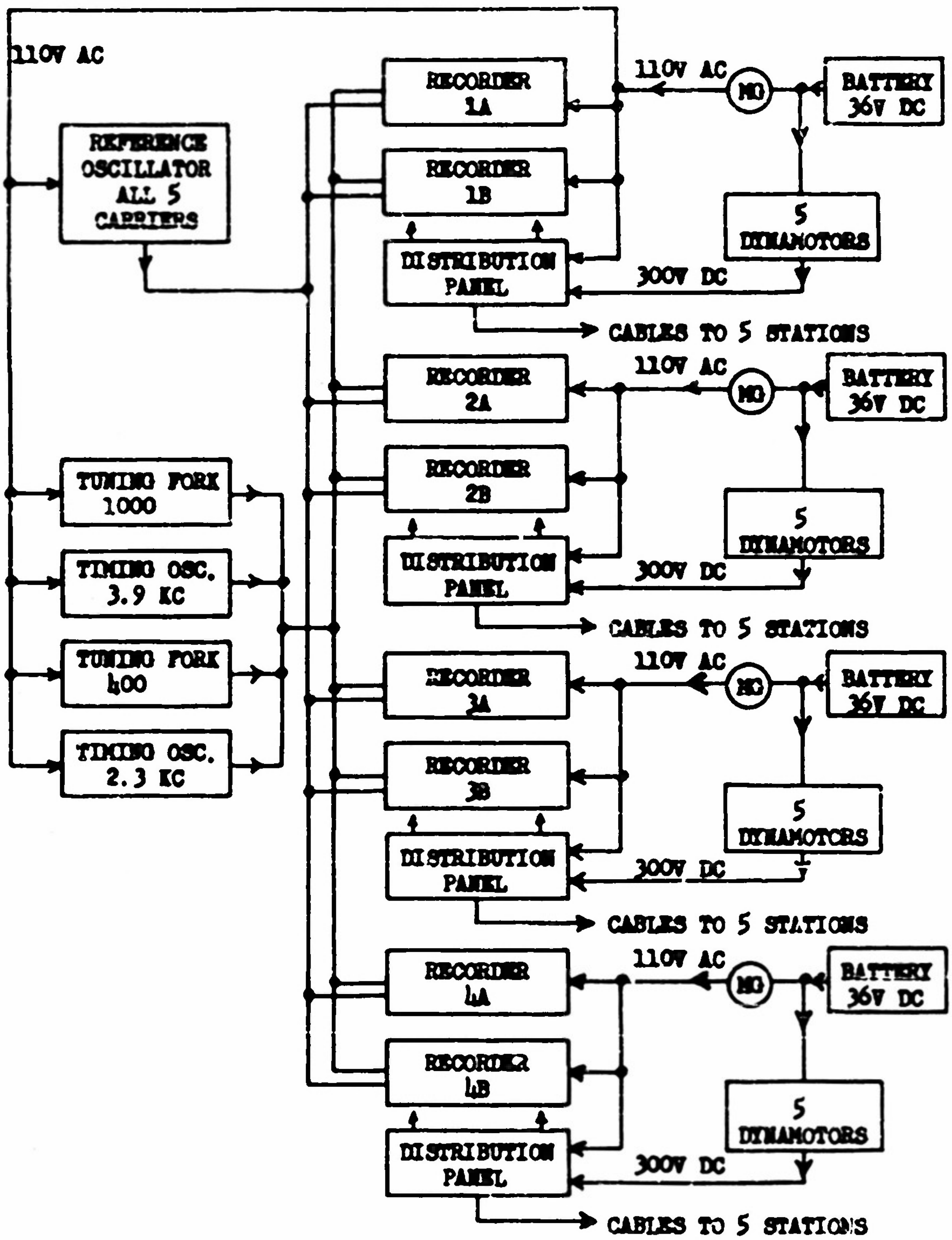


FIG. 5.4 OVER-ALL RECORDING SYSTEM

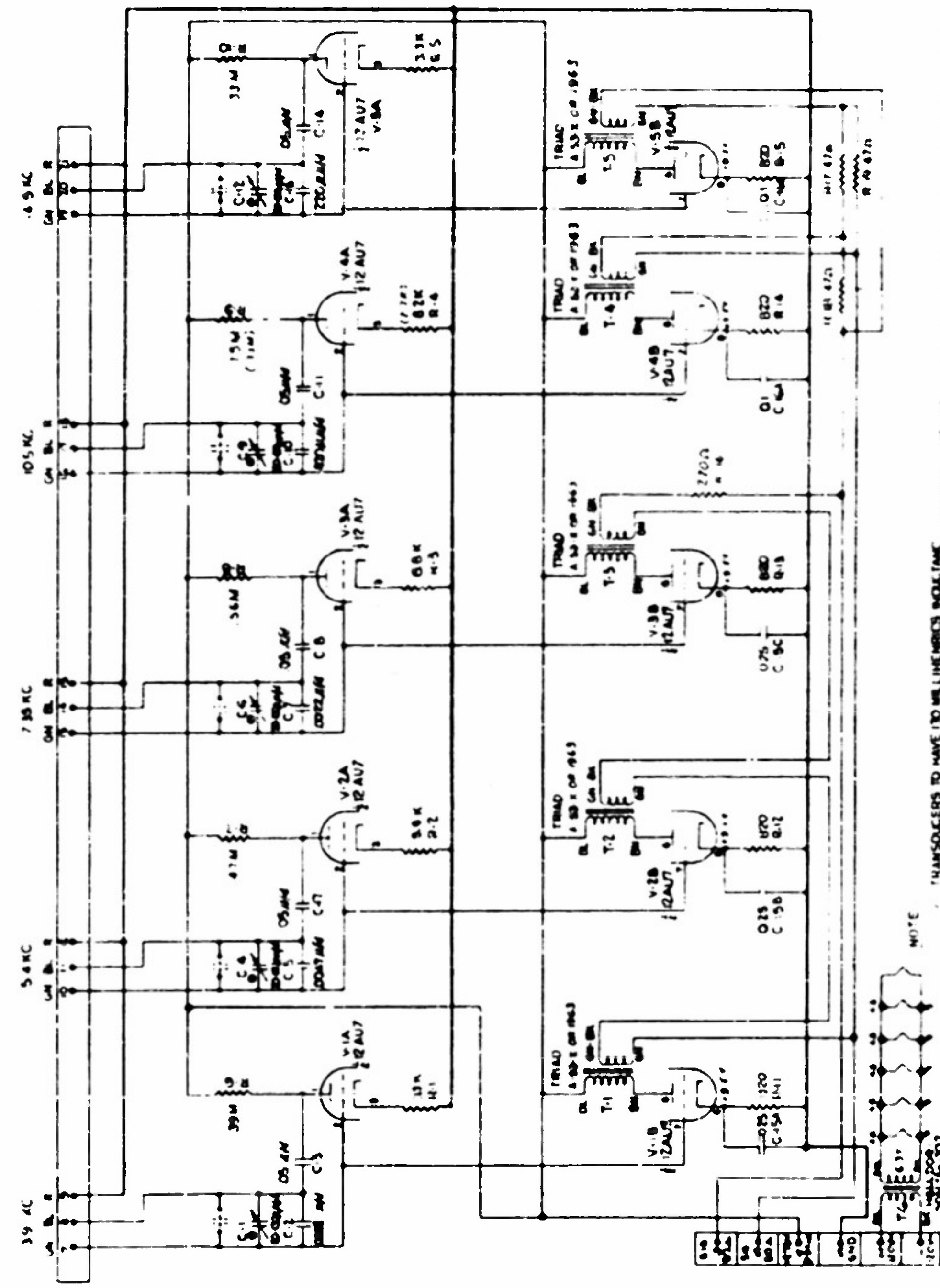


FIG. 5.5 OSCILLATOR-AMPLIFIER SCHEMATIC

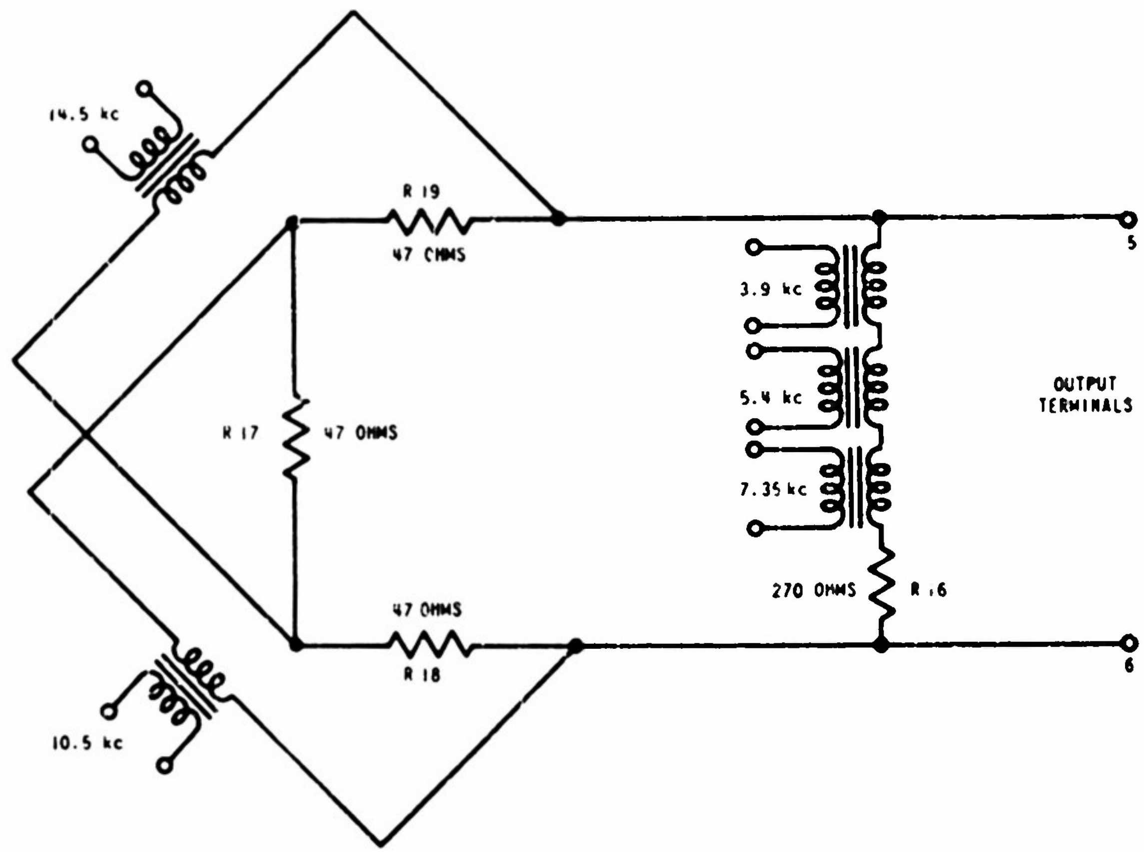


FIG. 5.6 BRIDGE CIRCUIT FOR COMBINED OUTPUT

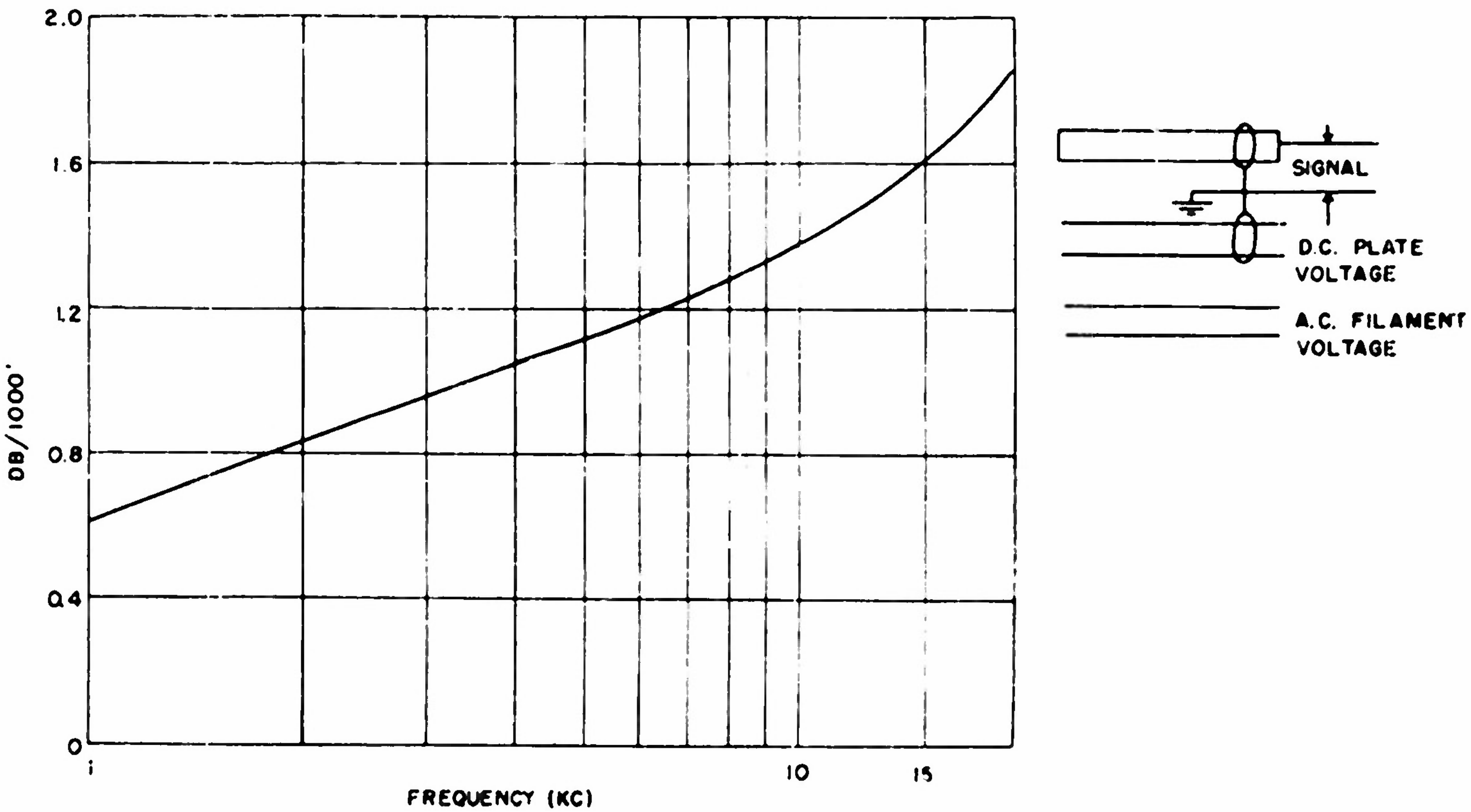


Fig. 5.7 Signal Attenuation in MCOS-6 Cable

Fig. 5.8 Cable Laying

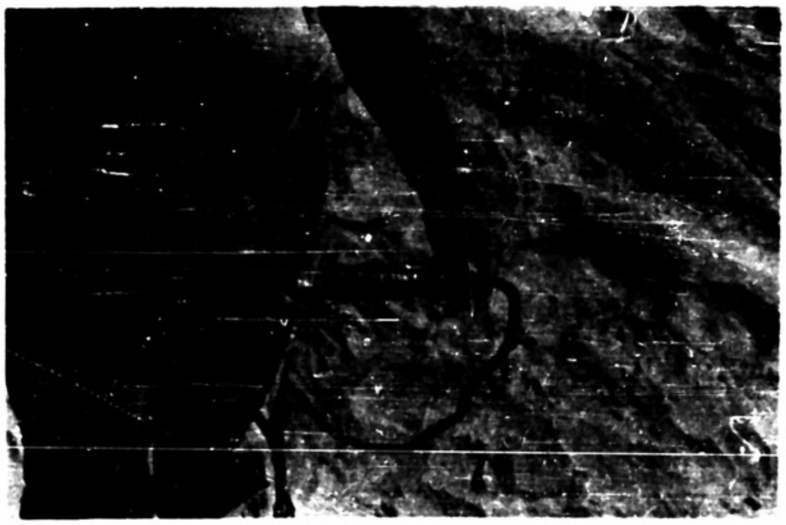


Fig. 5.9 Cable Connector

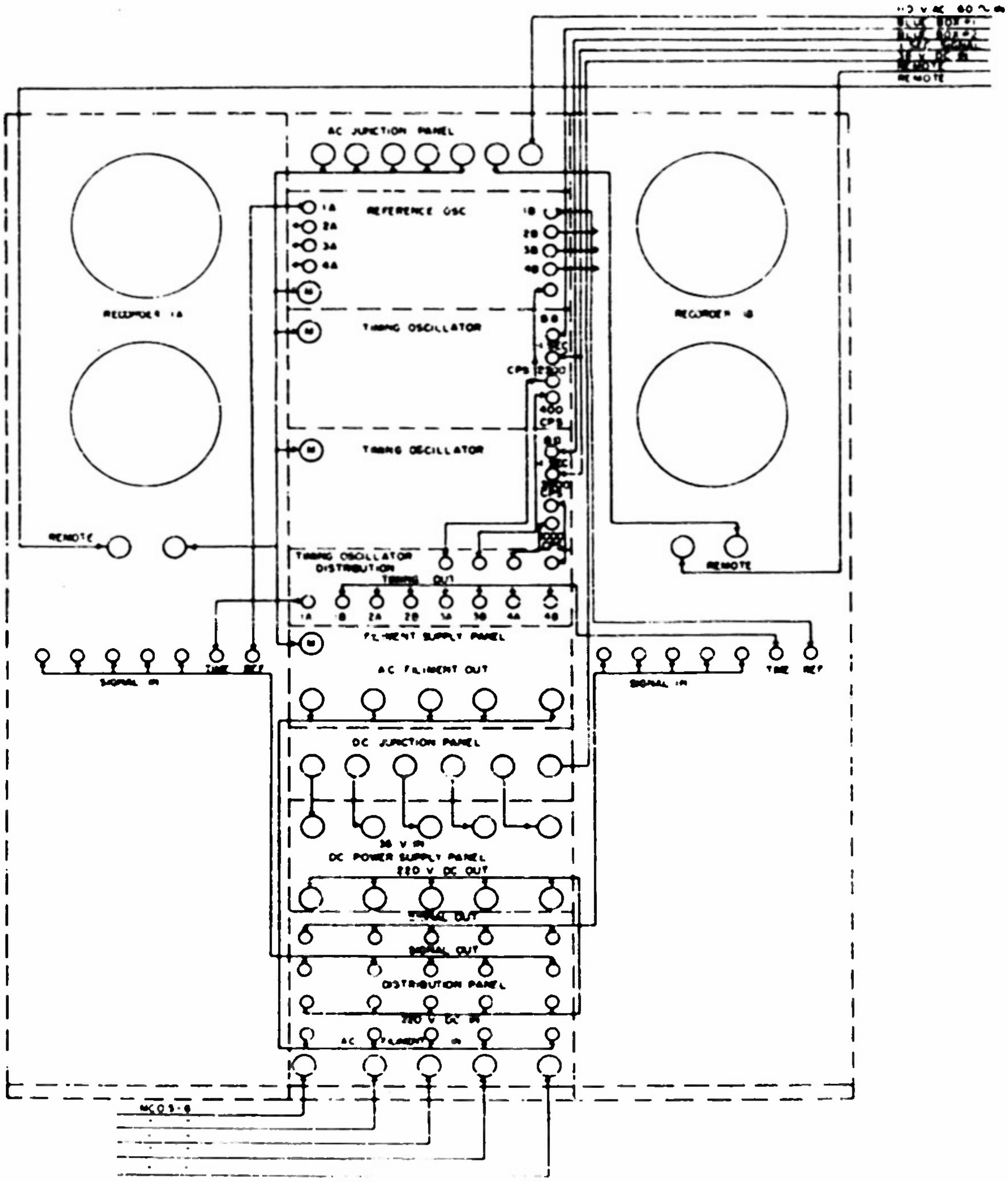


Fig. 5.10 Inter Cabinet Layout

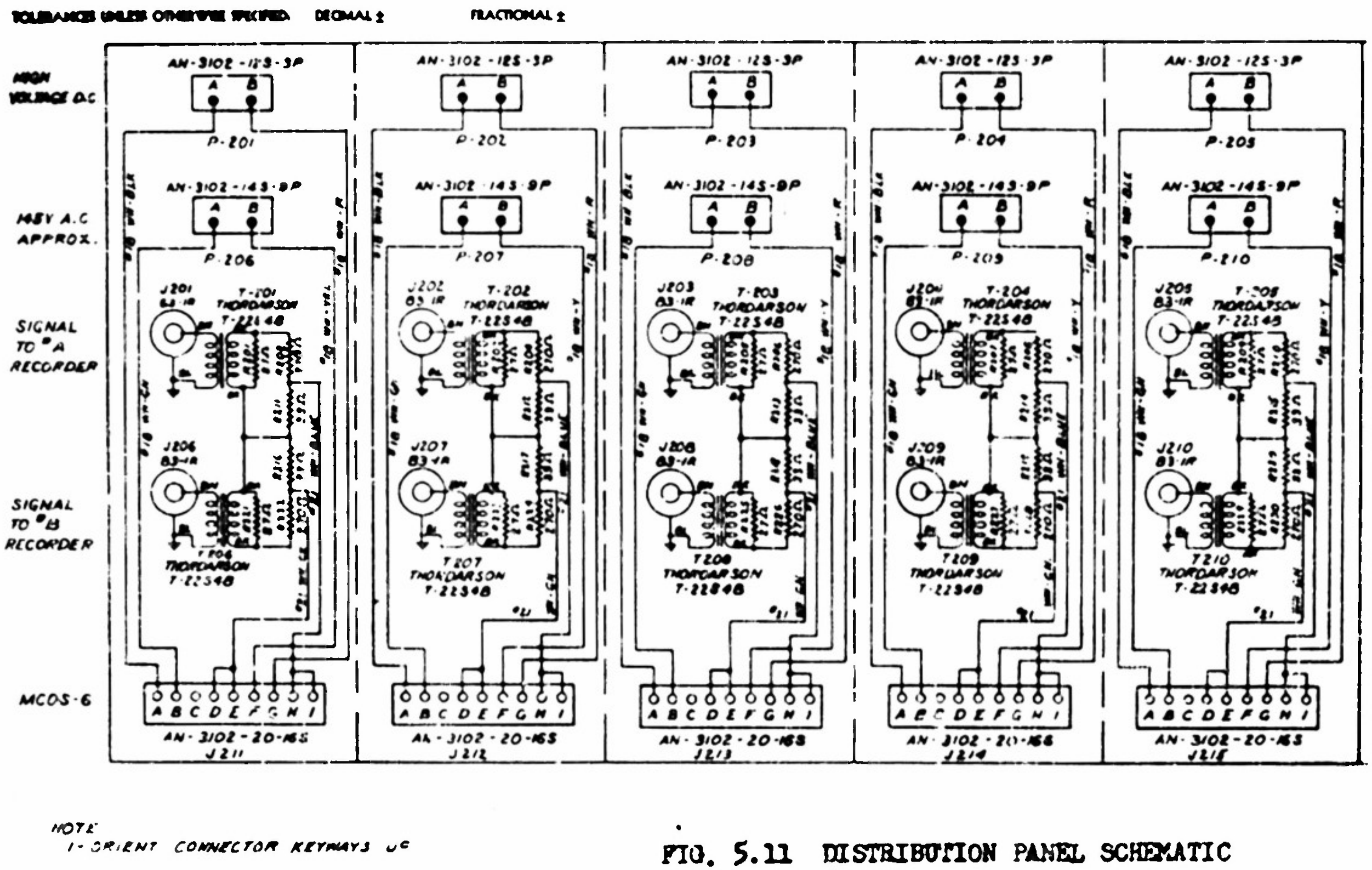
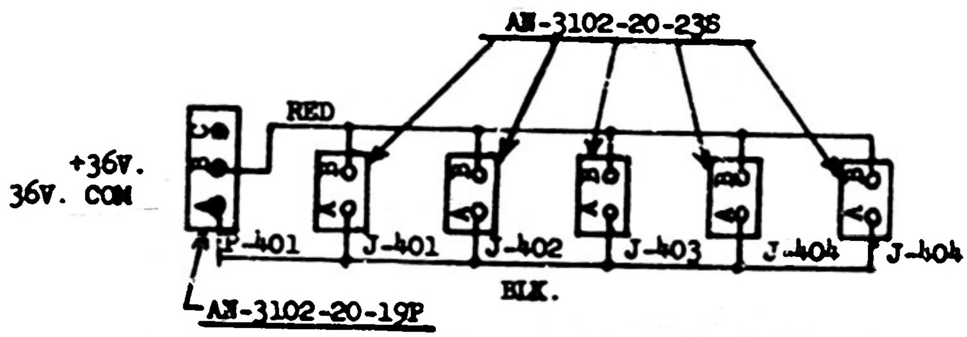
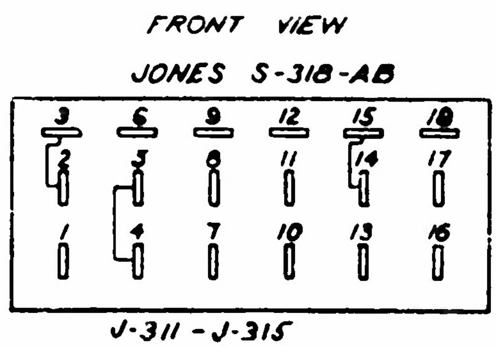


FIG. 5.11 DISTRIBUTION PANEL SCHEMATIC



NOTE:
1. - ORIENT CONNECTOR KEYWAYS UP

FIG. 5.12
D.C. POWER SUPPLY PANEL



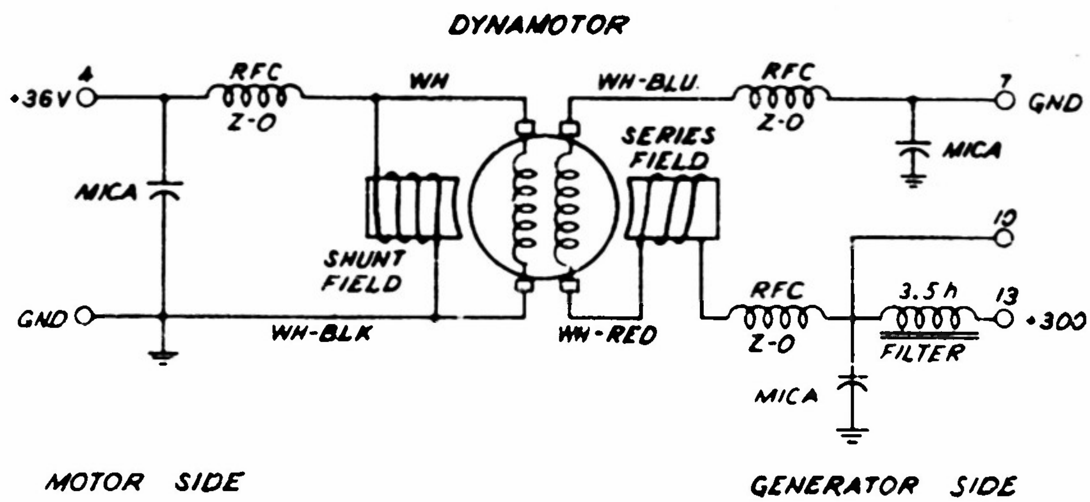
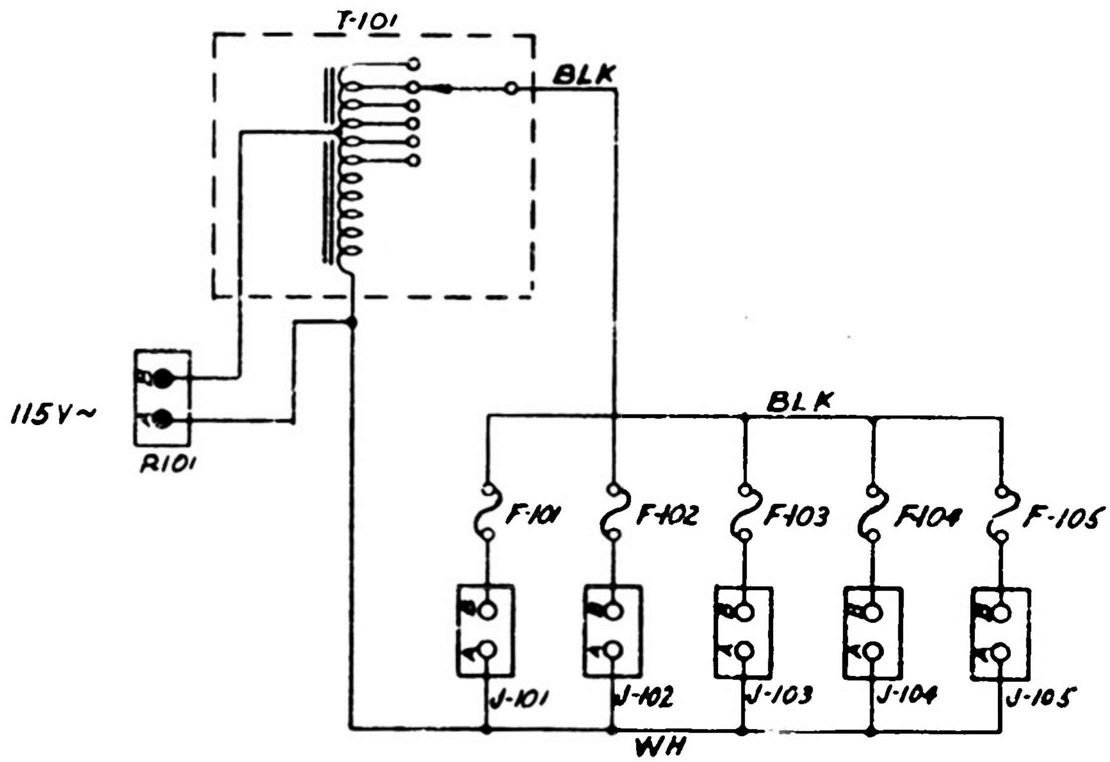


Fig. 5.13 Dynamotor Circuit



F-101 - F-105 $\frac{1}{2}$A SLO-BLO FUSE
J-101 - J-105 AN-3102-14S-9S
R101 AN-3102-20-23P
T-101 STANCOR P-6299

NOTE:
1 - ORIENT CONNECTOR KEYWAYS UP

Fig. 5.14 Filament Supply Panel

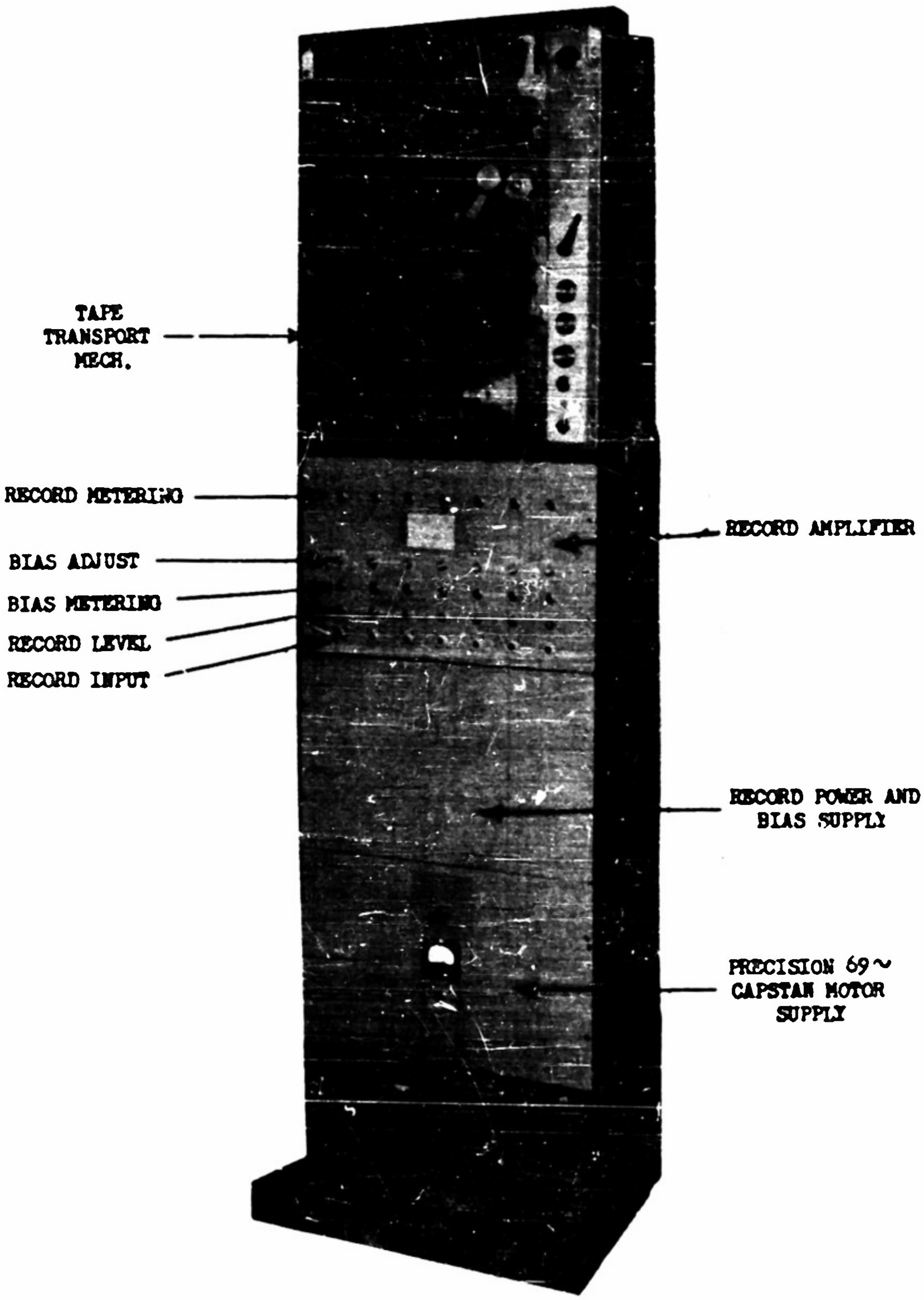


Fig. 5.15 Ampex Magnetic Tape Recorder

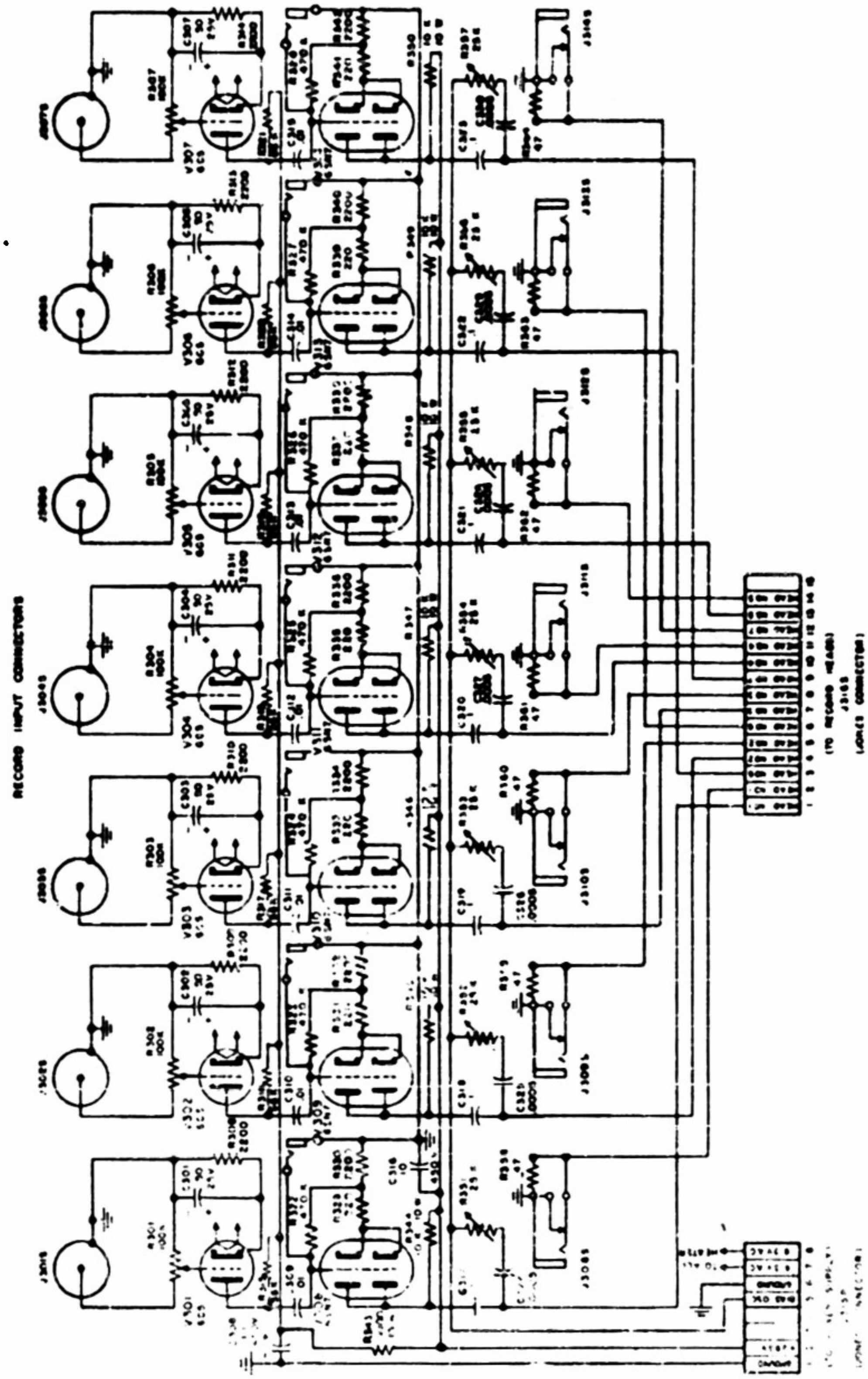


Fig. 5.16 Seven Channel Record Amplifier

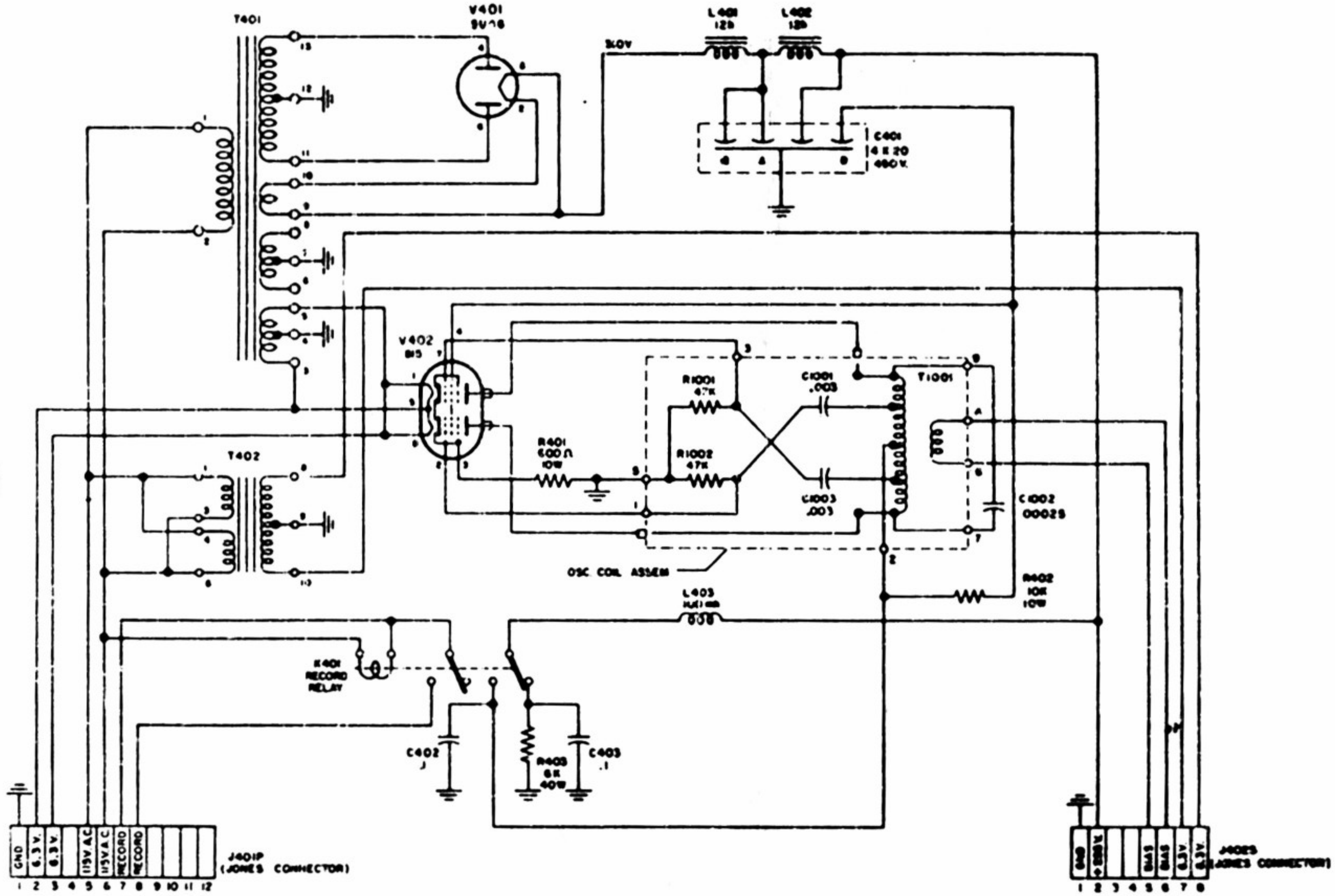
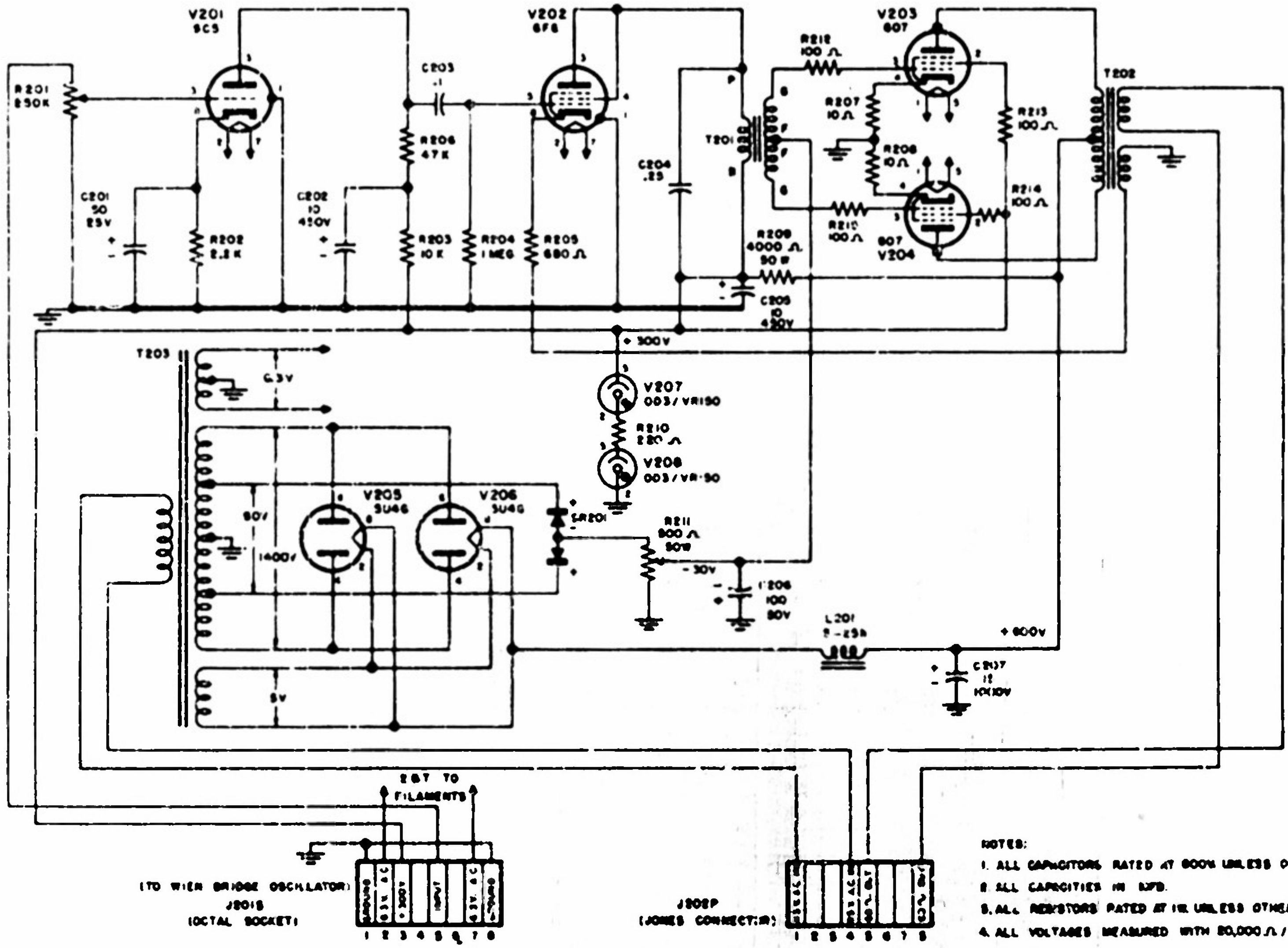


Fig. 5.17 Record Amplifier Power Supply and Bias Oscillator



NOTES:

1. ALL CAPACITORS RATED AT 600V UNLESS OTHERWISE STATED
2. ALL CAPACITIES IN MFD.
3. ALL RESISTORS RATED AT 1W. UNLESS OTHERWISE STATED
4. ALL VOLTAGES MEASURED WITH 20,000 Ω / VOLT METER

FIG. 5.18 POWER AMPLIFIER FOR CAPSTAN MOTOR SUPPLY

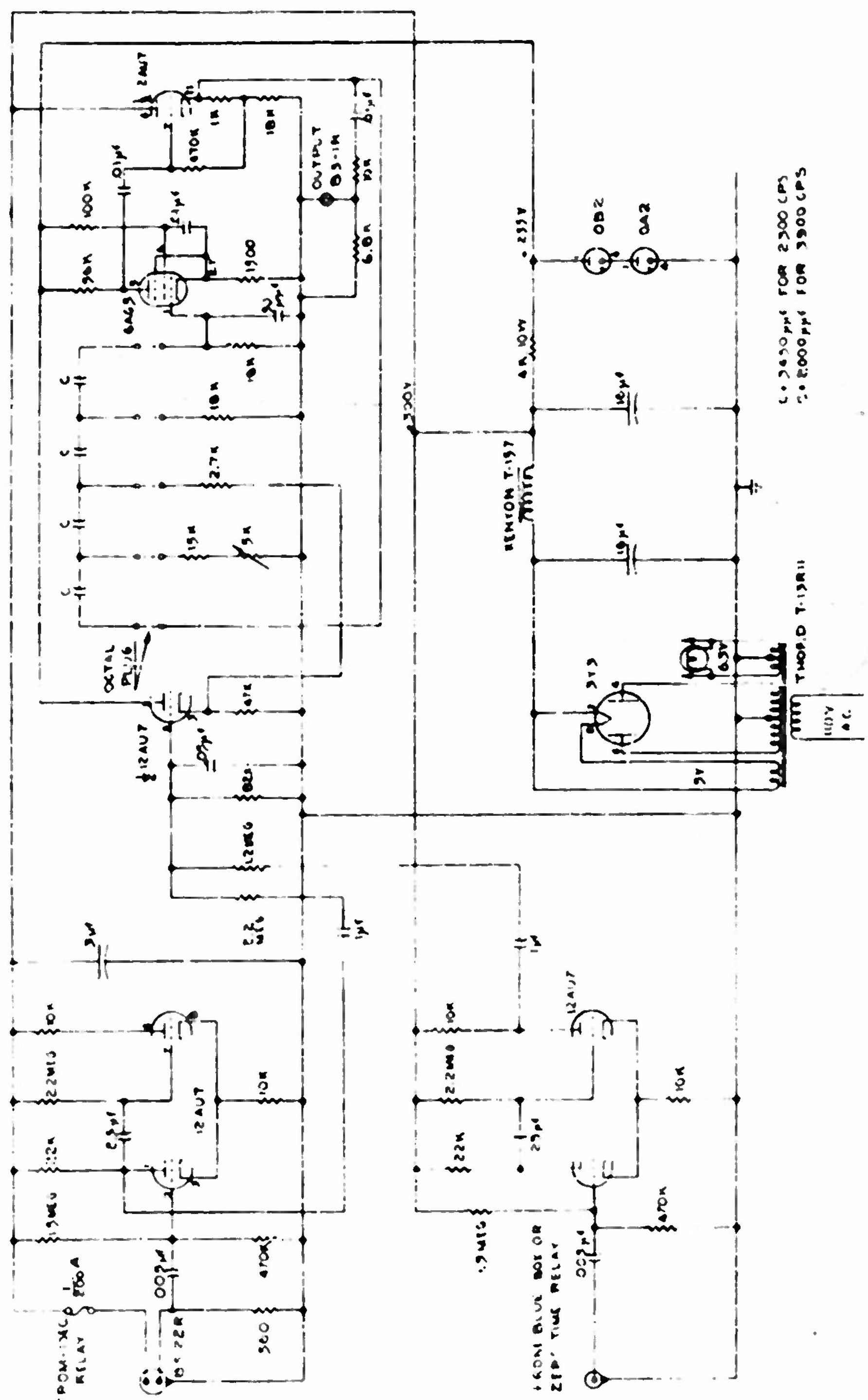
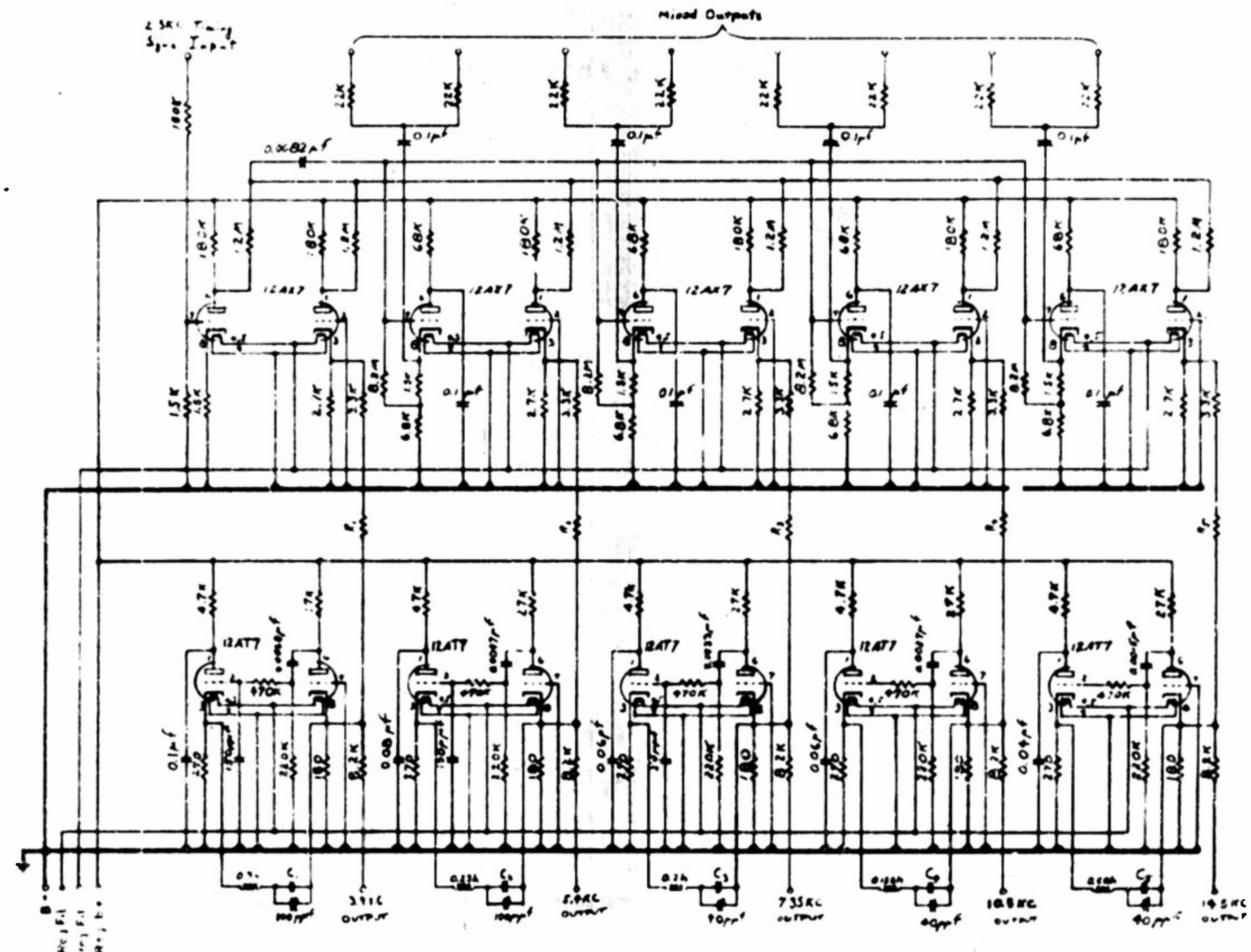


Fig. 5.19 Timing Oscillator



C_1 to C_5: chosen to give proper frequency in each case

R_1 to R_5: chosen to give 0.1v output across 100K load

FIG. 5.20 REFERENCE OSCILLATOR

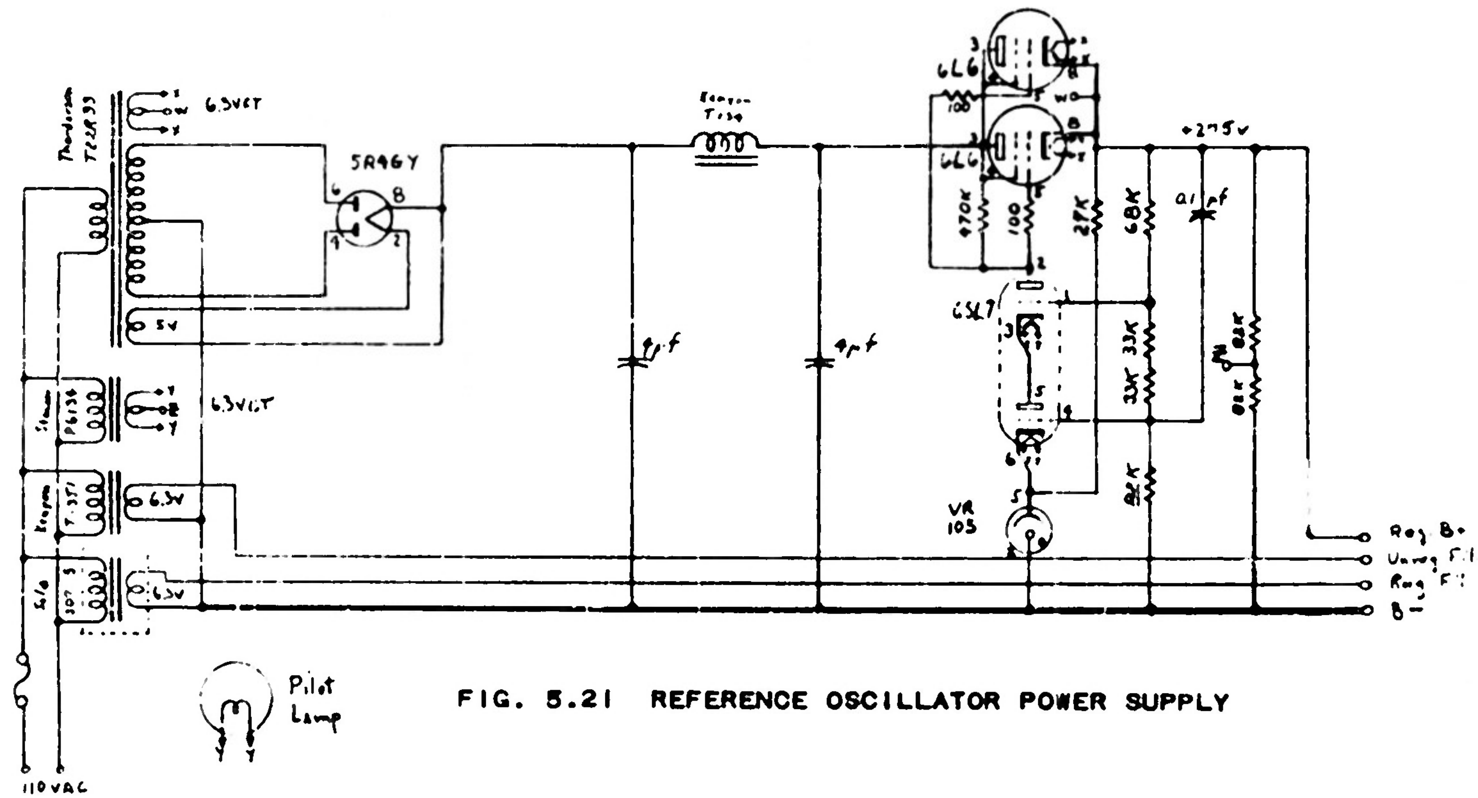


FIG. 5.21 REFERENCE OSCILLATOR POWER SUPPLY

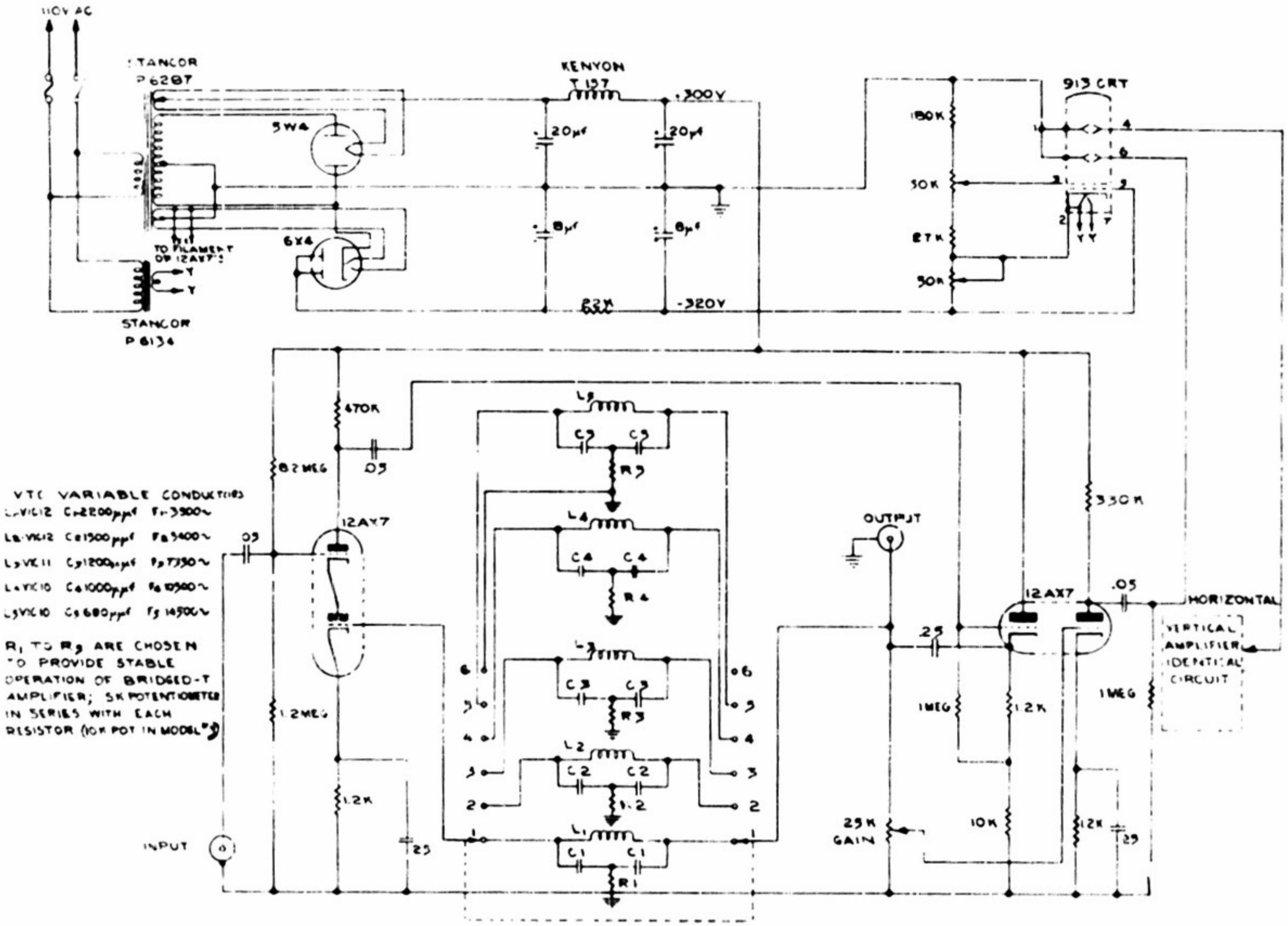


FIG. 8.22 FILTER SCOPE

Fig. 5.23 Field Cable Tester

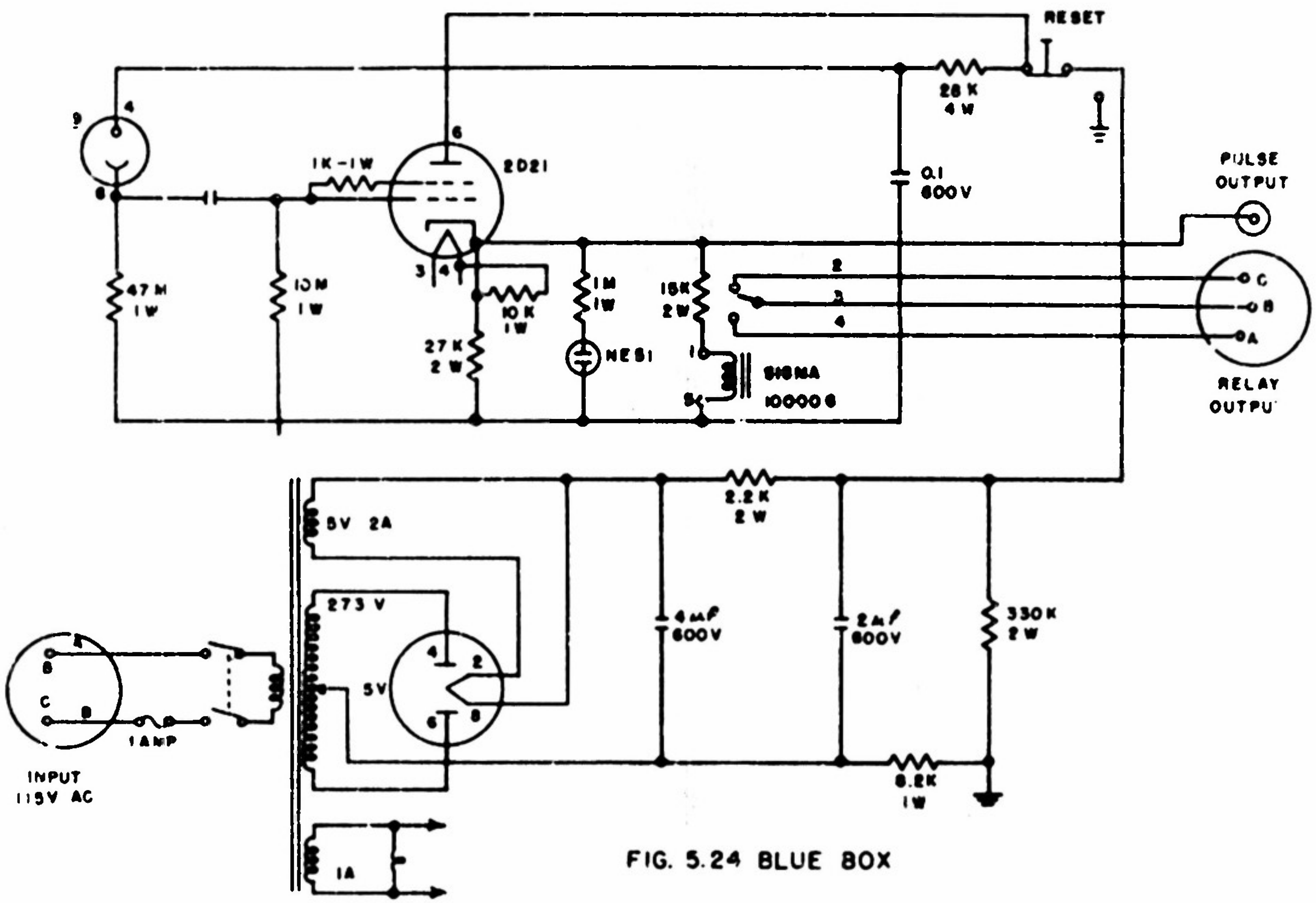


FIG. 5.24 BLUE BOX

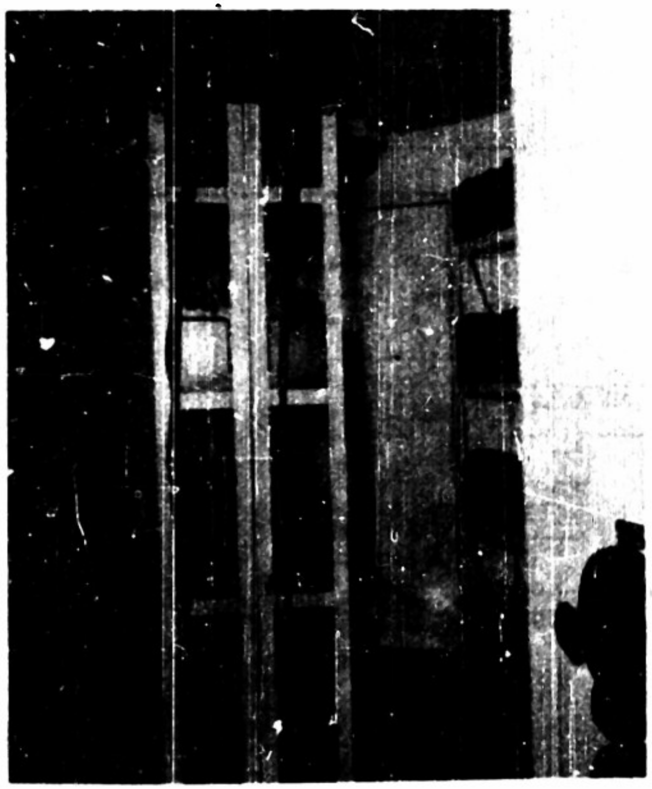


Fig. 5.25 Battery Bank in Trailer

Fig. 5.26 Motor Generator in Trailer

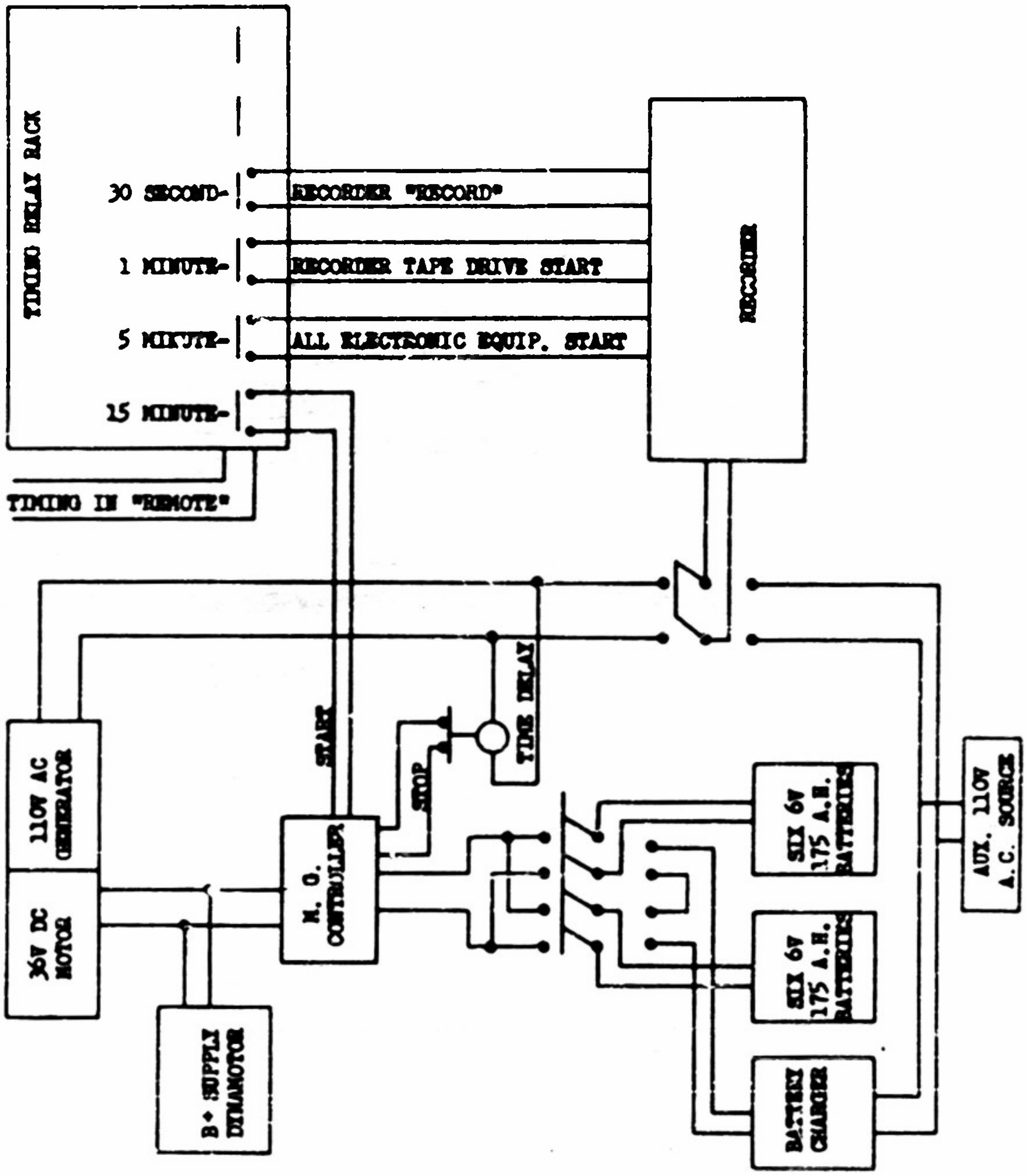


FIG. 5.27 POWER CONTROLS FOR TYPICAL BANK

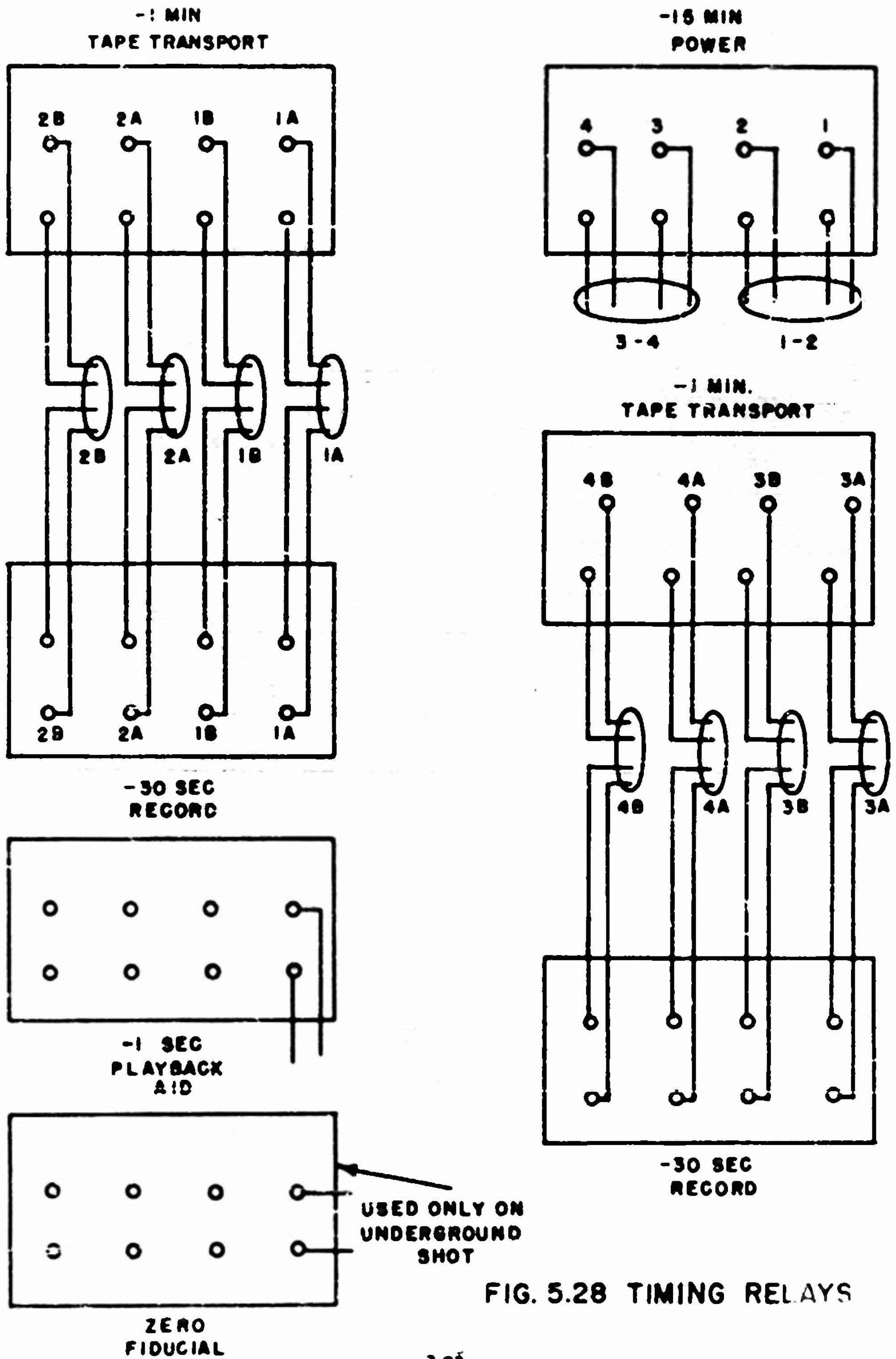


FIG. 5.28 TIMING RELAYS

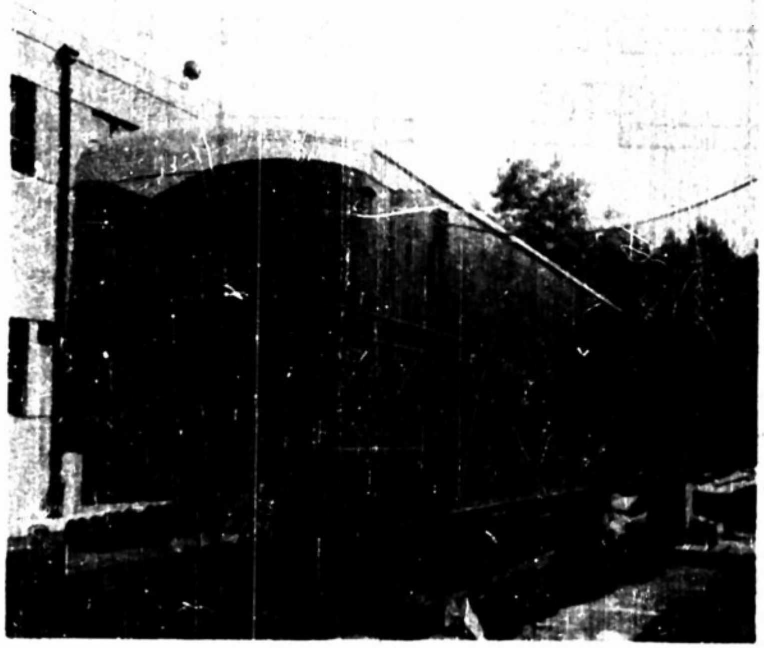


Fig. 5.29 Instrumentation Trailer

Fig. 5.30 Instrumentation Trailer
Inside - Towards Rear

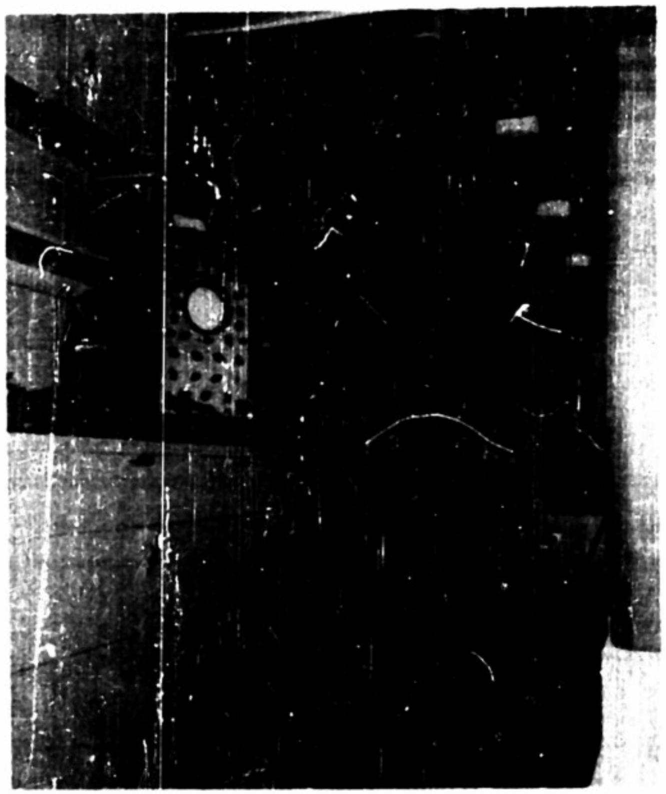


Fig. 5.32 Instrumentation Trailer
Inside - Left Side

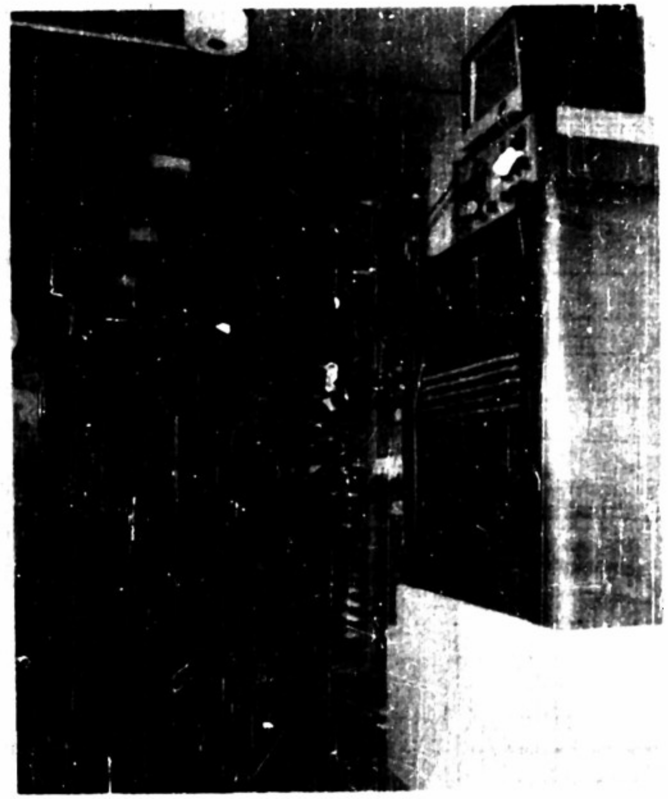


Fig. 5.31 Instrumentation Trailer
Inside - Right Side

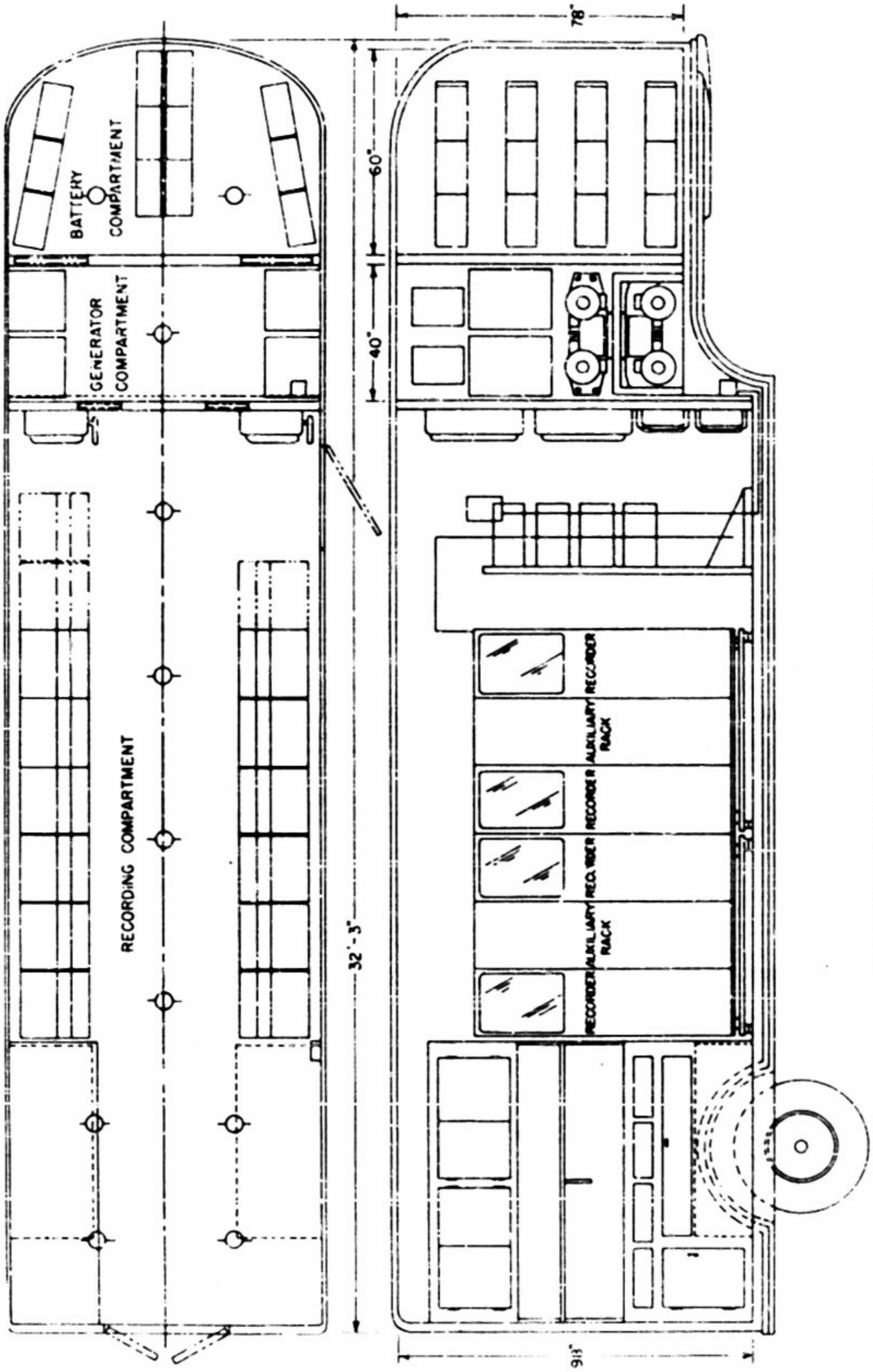


FIG. 5.33 INSTRUMENTATION TRAILER - LAYOUT

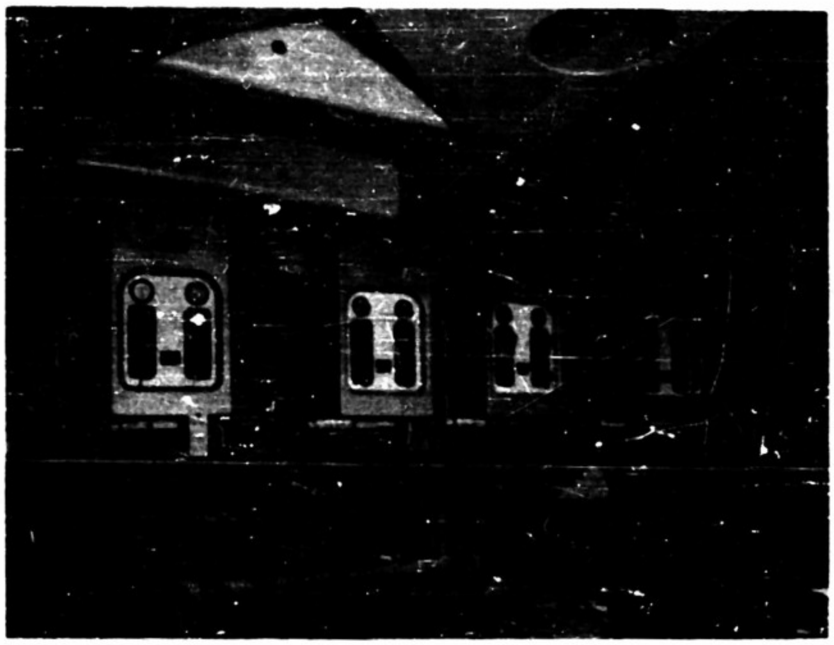


Fig. 5.34 Instrumentation Trailer - Battery Chargers

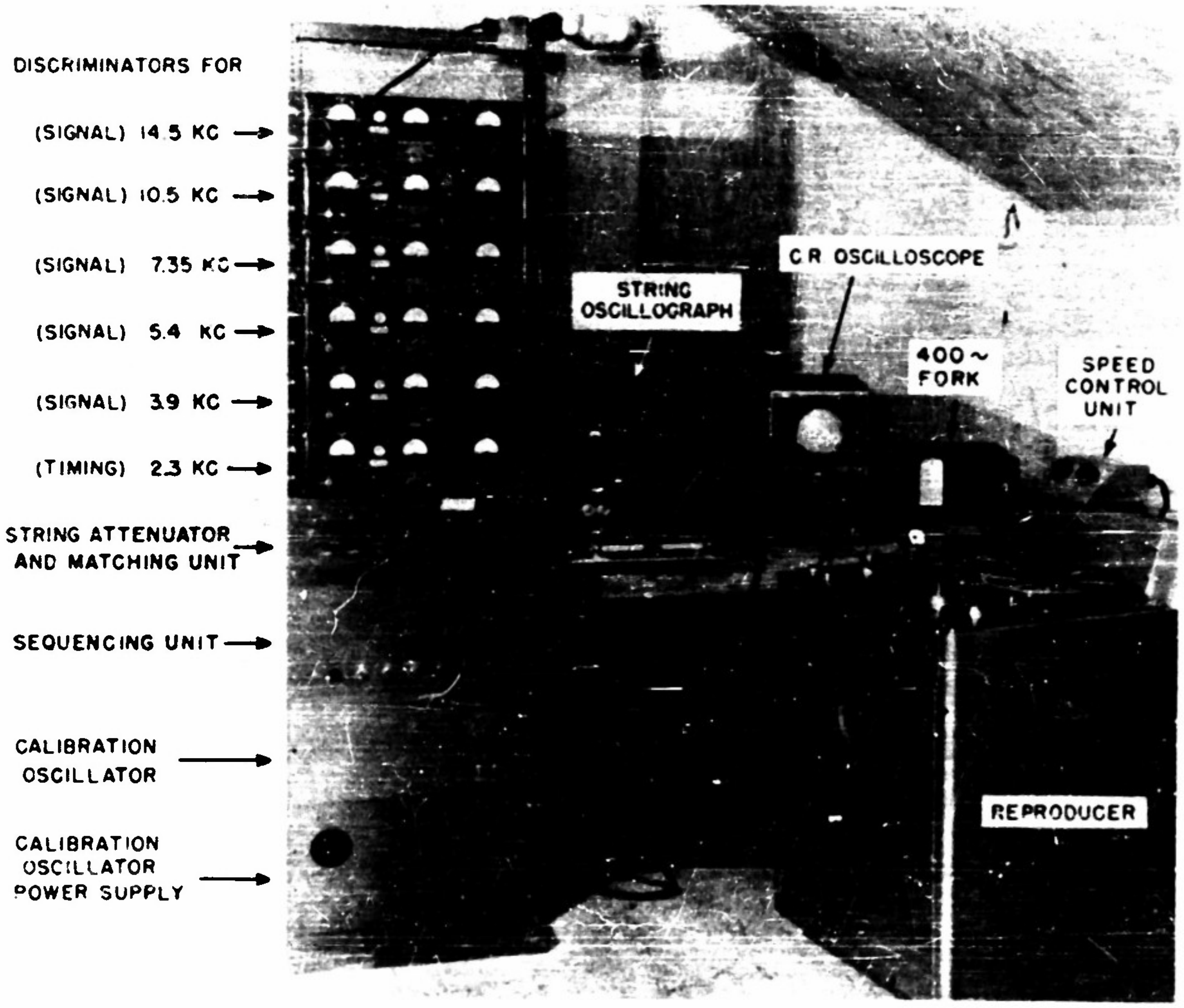


Fig. 5.35 Playback System

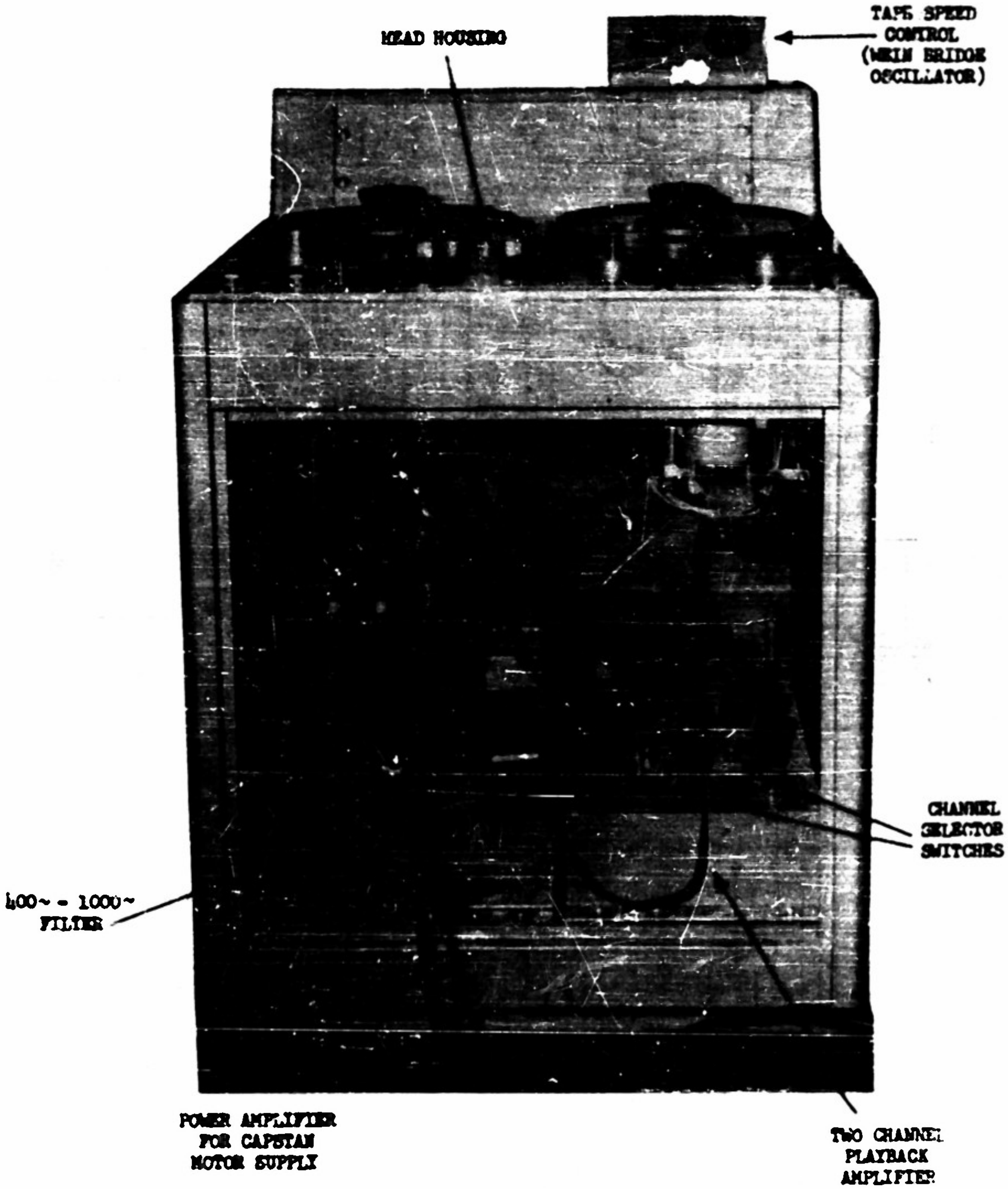


Fig. 5.36 Ampex Magnetic Tape Recorder

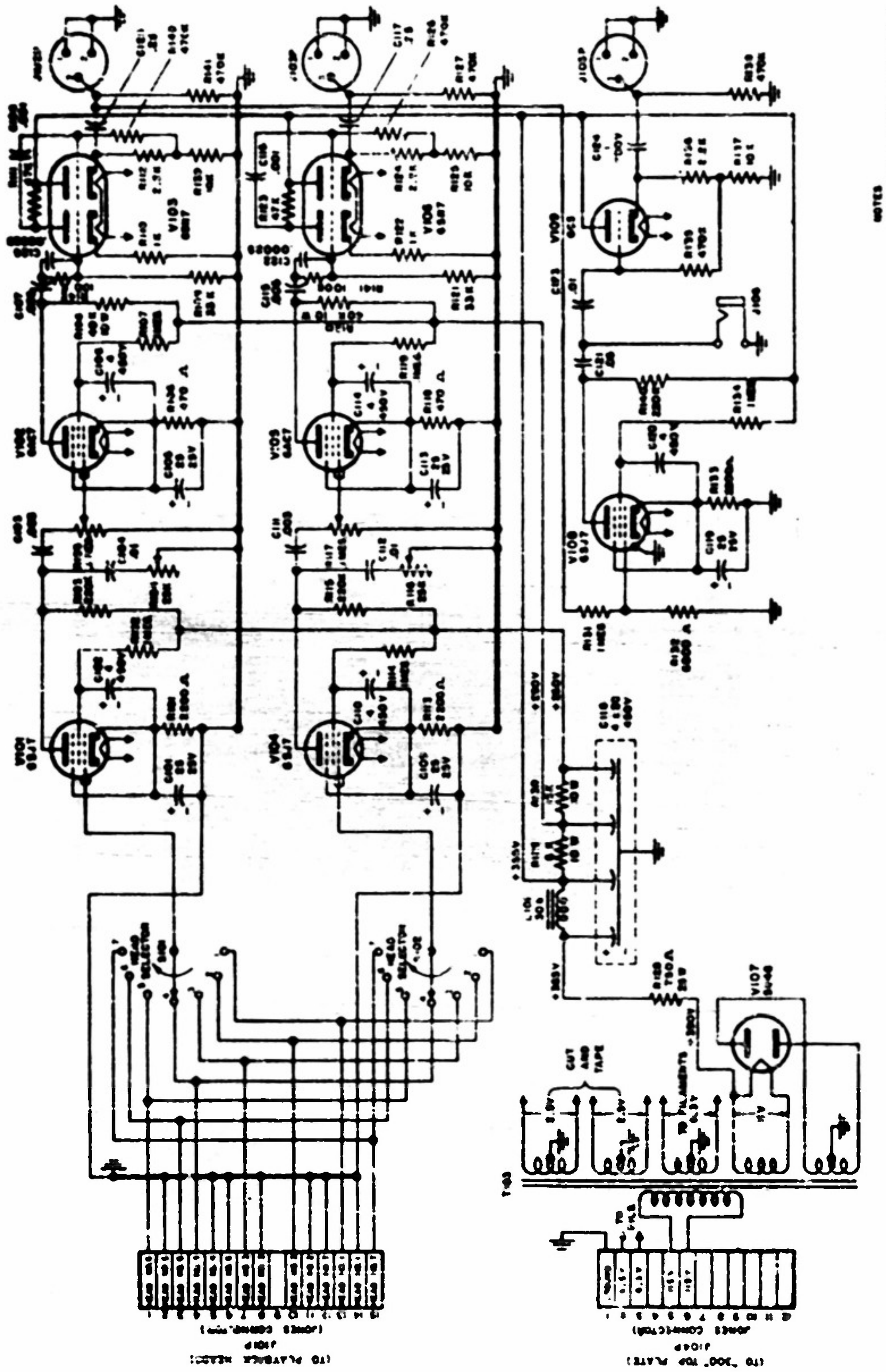
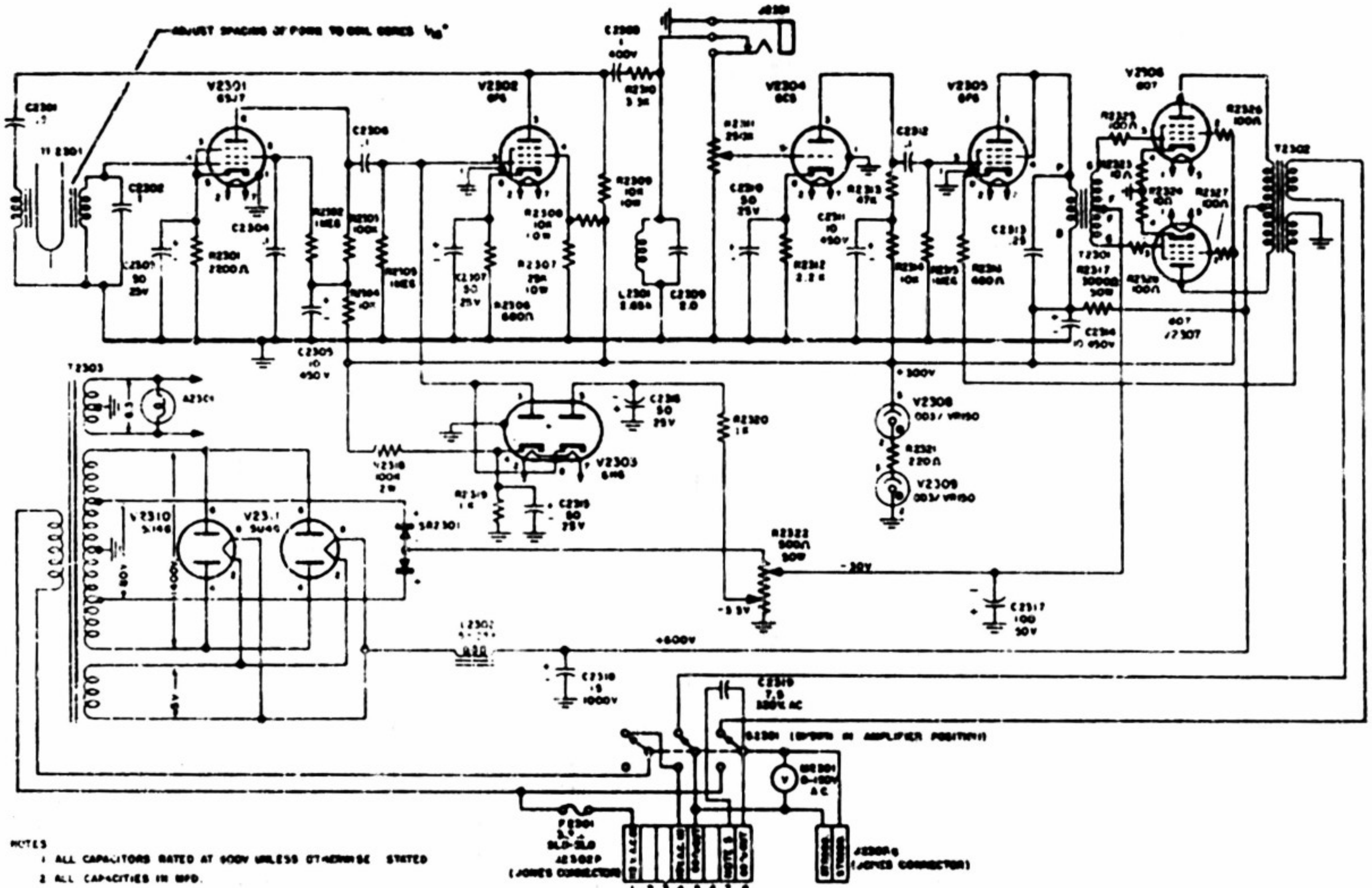
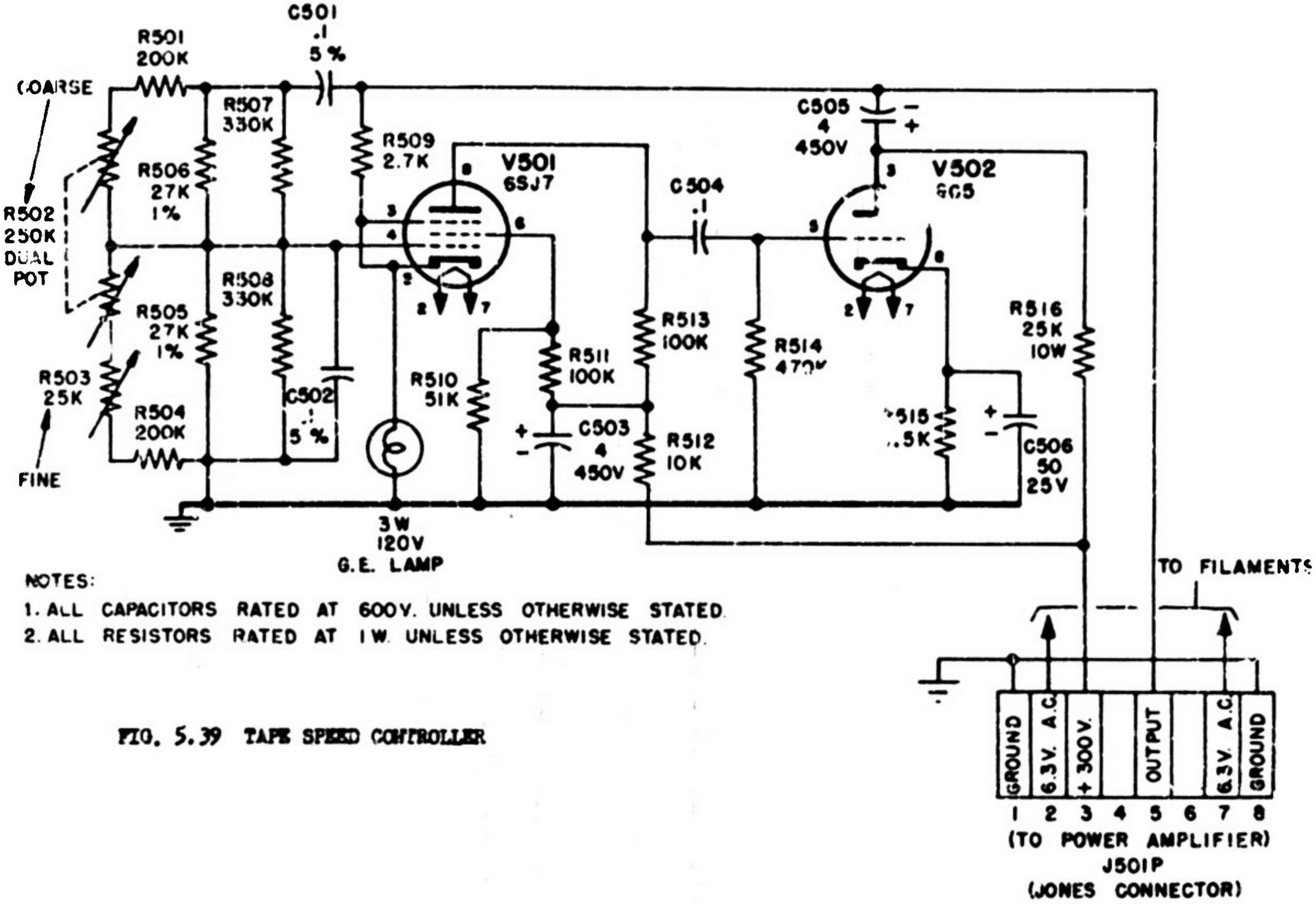


FIG. 5.37 PLAYBACK AMPLIFIER



NOTES
1 ALL CAPACITORS RATED AT 600V UNLESS OTHERWISE STATED
2 ALL CAPACITIES IN MFD.
3 ALL RESISTORS RATED AT 1W UNLESS OTHERWISE STATED
4 ALL VOLTAGES MEASURED WITH 20,000 Ω / VOLT METER
5 POW[illegible]CTOR CORRECTION CAPACITOR

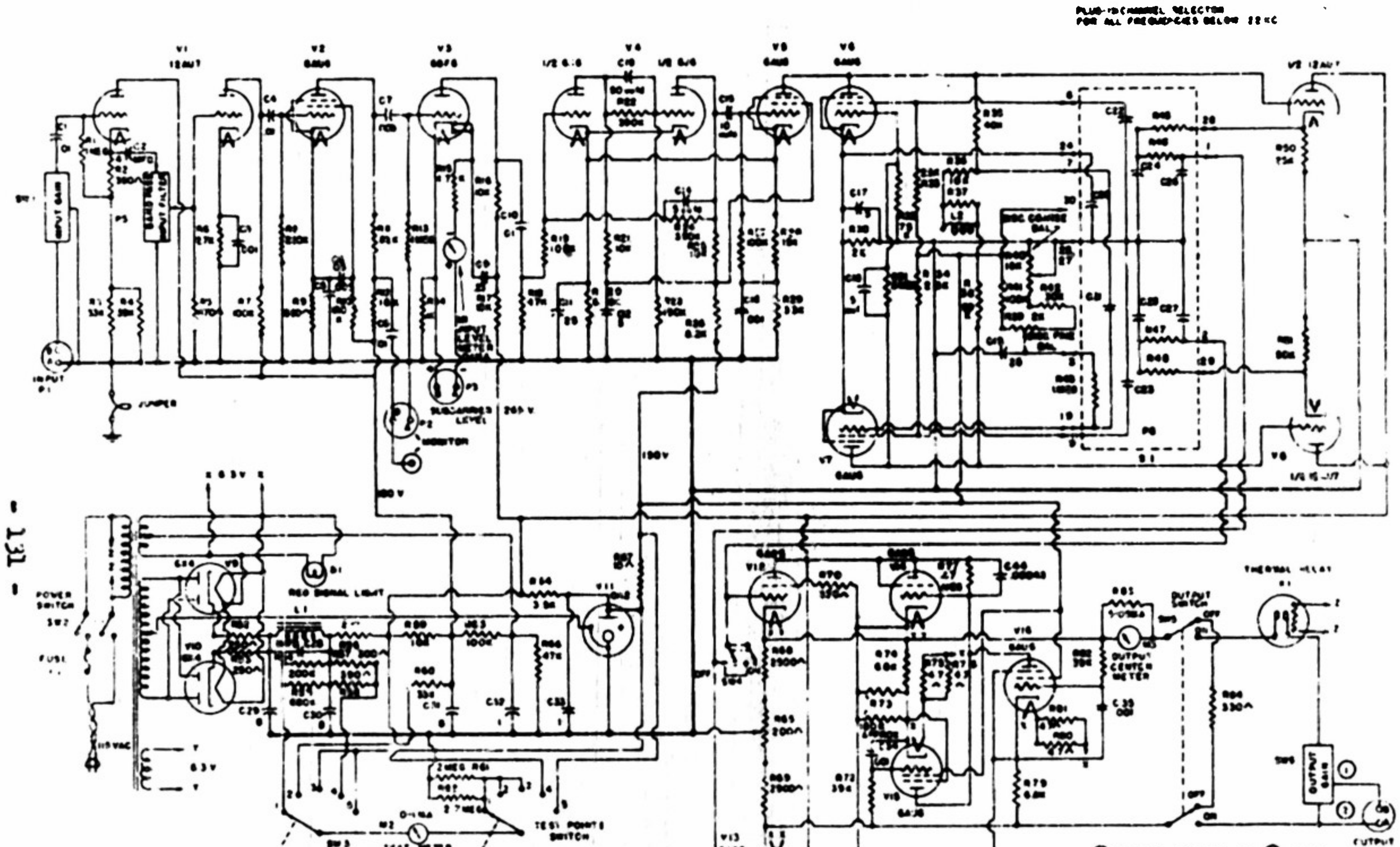
FIG. 5.38 69 CYCLE CAPSTAN MOTOR AMPLIFIER



NOTES:

1. ALL CAPACITORS RATED AT 600V. UNLESS OTHERWISE STATED.
2. ALL RESISTORS RATED AT 1W. UNLESS OTHERWISE STATED.

FIG. 5.39 TAPE SPEED CONTROLLER



CHANNEL NO	CARRIER CPS	MODULATION CPS	C20 MFD	C21 MFD	C22,23 MFD	C24,25 MFD	C26,27 MFD	R43 MEG	R46,48 1000 OHMS	R46,47 MEG
1	560	0-8.5	6.0	.0015	1.0	.05	.005	1	68	910
2	730	0-11	6.0	.001	.5	.03	.005	1	68	470
3	960	0-14.5	6.0	.0008	.5	.02	.003	1	68	390
4	1300	0-20	8.5	.0009	.22	.02	.002	1	68	200
5	1700	0-26	1.5	.00048	.22	.015	.002	1	68	270
6	2300	0-35	0.5	.00036	.22	.01	.002	1	68	330
7	3000	0-45	2.5	.00022	.1	.008	.0021	1	68	470
8	3900	0-60	0.5	.0002	.1	.007	.00243	1	68	680
9	5400	0-81	---	.00015	.1	.005	.00243	1	68	560
10	7350	0-112	---	.0001	.05	.003	.00042	1	68	390
11	10500	0-160	---	.00008	.1	.002	.0021	1	68	680
---	12300	0-190	---	.00006	.05	.002	.0001	1	68	560
12	14500	0-220	---	.00005	.02	.00145	.0001	1	68	470

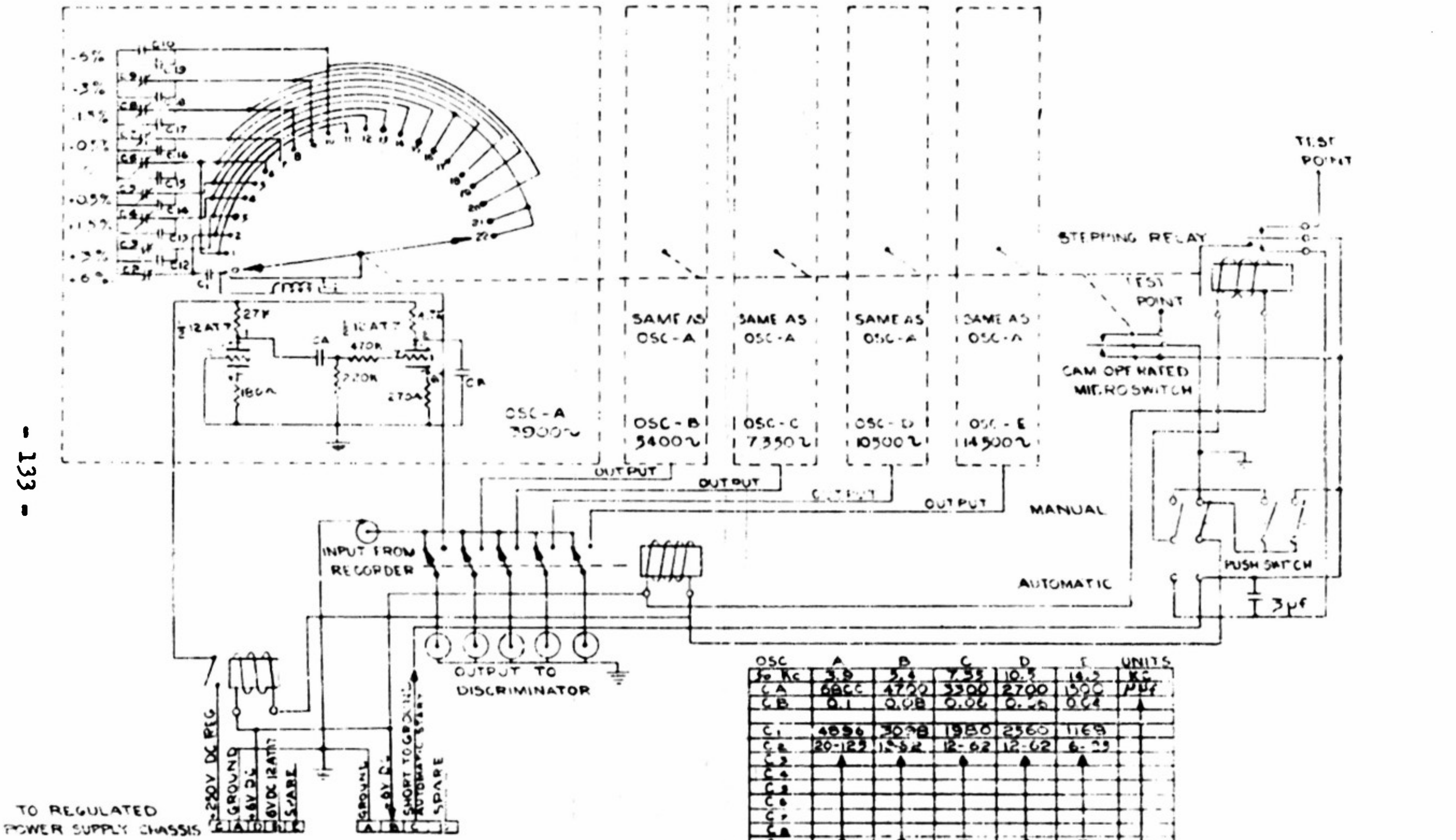
R57 ADJUSTED TO PROVIDE LINEARITY AT 7 KC

R72 & R78 ADJUSTED TO COMPENSATE FOR CIRCUIT TOLERANCES

① [illegible] WITH RESPECT TO ② WHEN FREQUENCY INCREASES FROM CENTER

Fig. 5.40 Discriminator

Fig. 5.41 String Galvanometer Oscillograph



OSC	A	B	C	D	E	UNITS
fo Kc	3.9	5.4	7.55	10.3	14.5	KC
CA	6800	4700	3300	2700	1500	µµf
CB	0.1	0.08	0.06	[illegible]	0.04	
C1	4856	3078	1980	2560	1169	
C2	20-125	12-62	12-62	12-62	6-25	
C3						
C4						
C5						
C6						
C7						
C8						
C9	20-125	12-62	12-62	12-62	6-25	
C11	280	183	125	151	82	
C12	447	281	188	232	120	
C14	551	348	234	288	150	
C15	604	382	257	316	120	
C16	660	418	279	343	180	
C17	773	489	329	404	220	
C18	930	600	404	496	247	
C19	1330	841	565	635	330	µµf
L1	0.3	0.21	0.2	0.08	0.06	H

FIG. 5.42 CALIBRATION OSCILLATOR

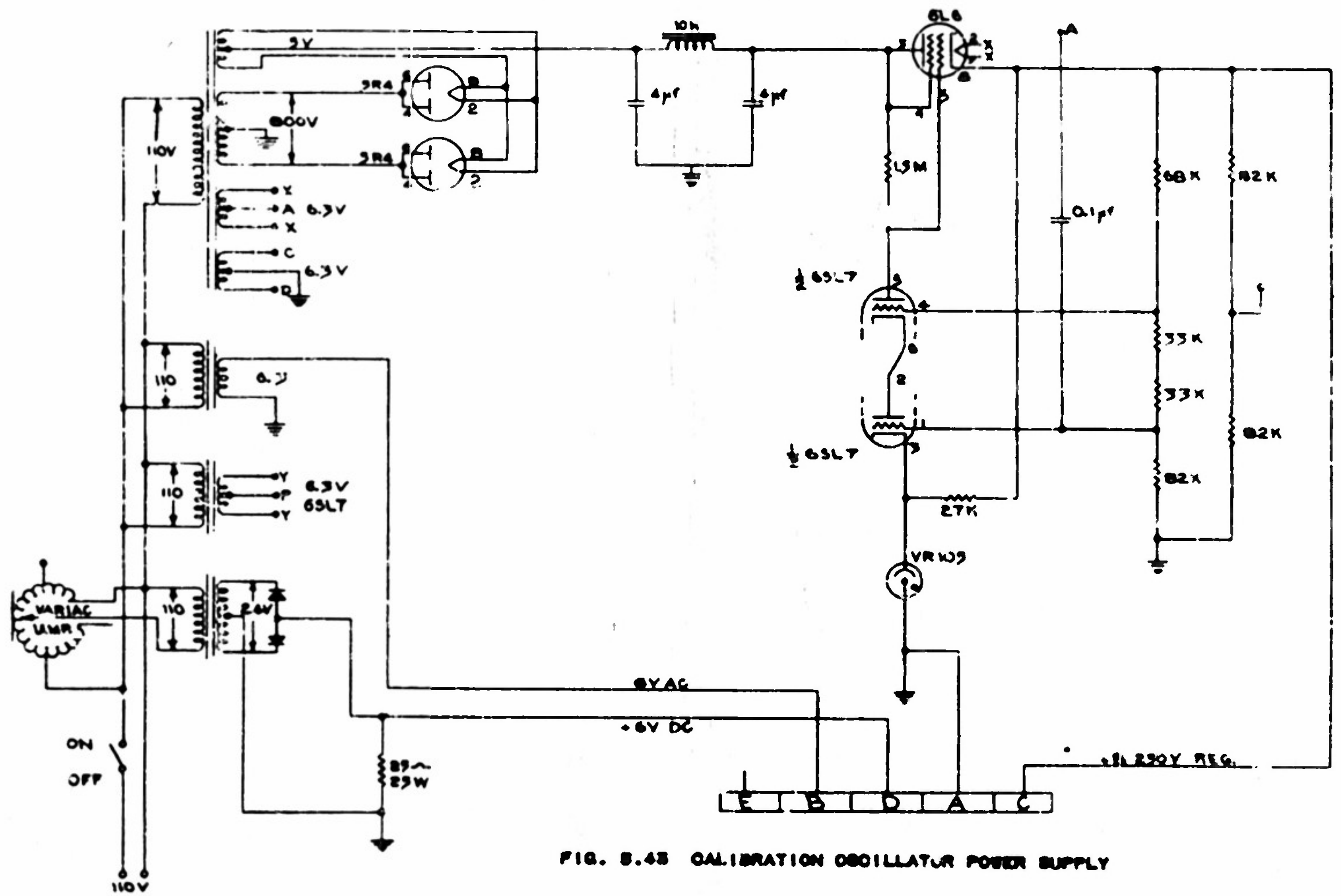


FIG. 5.48 CALIBRATION OSCILLATOR POWER SUPPLY

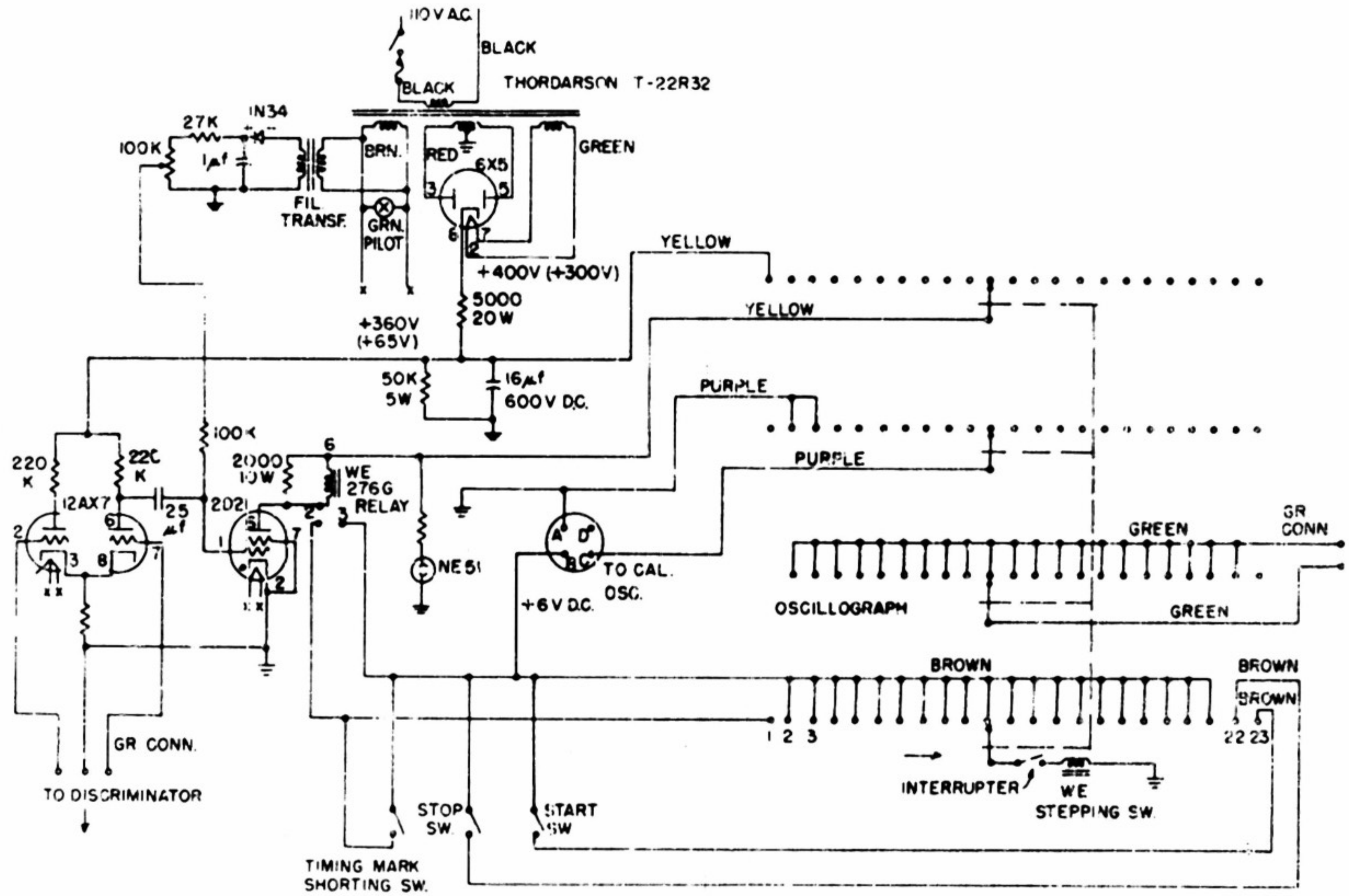


FIG. 5.44 SEQUENCING UNIT

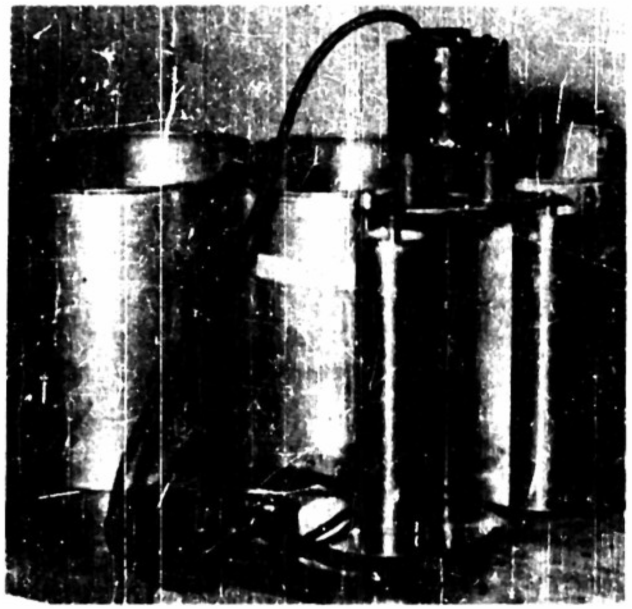


Fig. 5.45 Developing Tanks

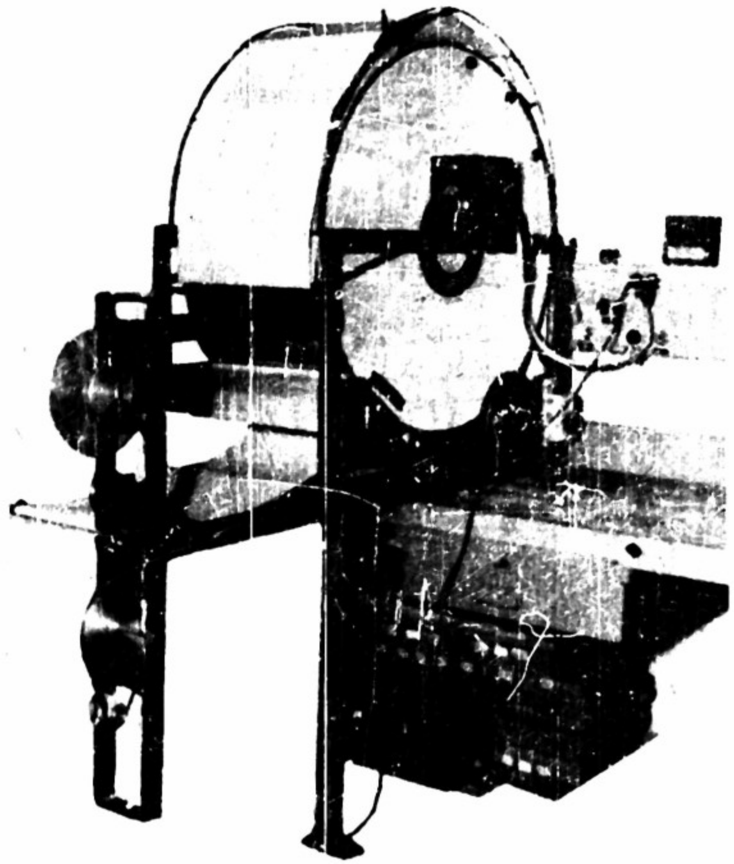


Fig. 5.46 Print Dryer

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